Westinghouse

AD669917

80133F-2

Submitted to: Office of Naval Research
Department of the Navy
Washington, D. C. 20360
Under contract N00014-67-C-0274

15 March 1968

Robert R. Morgan

PREPARATION OF A WORLDWIDE VLF EFFECTIVE CONDUCTIVITY MAP

Westinghouse Electric Corporation
Environmental Science and Technology Department

ABSTRACT

A map showing effective electrical earth conductivity values for a propagating wave at VLF (10 kHz to 30 kHz) has been prepared for the major land areas of the world. Land area conductivity determinations were in most cases based upon known geological and climatological information. Actual conductivity data was collected where possible to aid in determining regional effective conductivity values, but the correlation between geology (and other known factors), and conductivity was used in estimating conductivity for the majority of the land areas.

The conductivity data are overprinted on seven 17 X 22 inch base maps which are separate from this report. Effective conductivity values are designated by numbers from 1 to 10 referenced to a legend on each sheet. Page-size maps showing a confidence factor and a variability factor are included in this report (Addendum).

A measurement program to establish the reliability of the map and to supplement estimates where the geology-conductivity correlation is not well known is recommended. A research program is also suggested to upgrade and improve the maps.

LIST OF ILLUSTRATIONS

TABLE OF CONTENTS

1.0 INTRODUCTION

A map showing effective electrical conductivity of the earth at very low frequencies (10 kHz to 30 kHz) has been prepared to aid in radio propagation and navigational studies. Explanatory material relating to the description and use of the map is included in this report as an Addendum. It is the major objective of this report to present information relating to the geology-conductivity correlation on which the map was based and the data collection effort. Specific recommendations are also presented for field measurements and a research program to up-grade and improve this first map. A note on the calculations of effective conductivity for a two-layer conducting earth, a bibliography of permafrost and its electrical properties, and a list of contributors to the map are included as appendices.

2.0 DATA COLLECTION EFFORT

Data was collected through a library search, personal contacts, personal letters, and by inquiries sent through the U. S. embassies throughout the world. Most of the inquiries during the initial stage of the program were through personal letters sent directly to private organizations within the foreign countries of interest. Later, assistance by the U. S. Department of State (arranged by NRL) allowed U. S. embassies to aid in contacting appropriate foreign government departments. This proved to be a more efficient means of collecting available information.

Table I shows the number of letters sent to embassies, government agencies, universities and institutions, private companies and persons, and the number of responses to these letters by country. Correspondence consisting of several letters with one institution or organization is counted as only one response. Additional letters which were later sent to addresses provided by the responses shown in this table are not included as part of this tabulation. About 40% of the inquiries sent in the first mailing received a response. Follow-up work netted additional fruitful information. Appendix C is a list of the contributors who sent useful information. In addition, a considerable amount of information was obtained through the library search. Because of the importance of permafrost in radio propagation studies, a bibliography was collected on the subject of permafrost and its electrical properties, and is included as Appendix B to this report.

TABLE I

Country	No. of Letters to Embassies	No. of Letters to Government Agencies	No. of Letters to Universities and Institutions	No. of Letters to Private Companies and Persons	No. of Responses to Letters Sent
Algeria	1	4	1		1
Angola		3		2	1
Bechuanaland		1			1
Cameroon	1	1			1
Central African Republic	1	1			1
Chad	1	1	1		1
Congo		5	2		1
Ethiopia	1	2	1		3
Gabon	1	3			2
Gambia	1				1
Ghana	1	1	1		1
Guinea	1	2	1		1
Portuguese Guinea		1			
Spanish Guinea					
Ivory Coast	1	3	1		1
Kenya	1	3	3		4
Liberia	1	1			1
Libya	1	3		1	1
Madgascar	1	1	2		1
Mali	1	2			
Mauritania	1	3			1
Morocco	1	10	2	1	4
Mozambique		1			
Niger	1	1			1
Nigeria	1	6	5	29	7
Nyasaland		1			
Northern Rhodesia		2			1

Table I (continued)

Country	No. of Letters to Embassies	No. of Letters to Government Agencies	No. of Letters to Universities and Institutions	No. of Letters to Private Companies and Persons	No. of Responses to Letters Sent
Southern Rhodesia		1	1		1
Ruanda-Urundi (Rwanda)	1	10	2		5
Republic of South Africa	1	5	8		11
Senegal	1	2	1		4
Sierra Leone	1	1	1		3
Somalia	1	3		1	2
French Somaliland		1		1	1
South-West Africa		1			
Sudan	1	1	1		1
Swaziland		1			1
Tanganyaka		2			
Togo	1	1			1
Tunisia	1	2		1	1
Uganda	1	1	1		2
United Arab Republic	1	7	2		2
Upper Volta	1	1			
Zambia					1
Afghanistan	1				
Argentine	1				1
Austria	1				1
Belgium	1				
Bolivia	1				
Brazil	1				
Bulgaria	1				
Burma	1				
Burundi	1				1

Table I (continued)

Country	No. of Letters to Embassies	No. of Letters to Government Agencies	No. of Letters to Universities and Institutions	No. of Letters to Private Companies and Persons	No. of Responses to Letters Sent
Ceylon	1				1
Chile	1				
China					
Columbia	1				
Costa Rica	1				1
Cuba					
Cyprus	1				1
Czechoslovakia	1		1		1
Denmark	1				
Dominican Republic	1				1
Ecuador	1				
El Salvador	1				1
Estonia					
Finland	1				
Formosa	1				1
France	1	1		2	1
Germany	1				
Great Britain and Northern Ireland	1	4			3
Greece	1				1
Guatemala	1				1
Haiti	1	1			1
Honduras	1				
Hungary	1	2			1
Iceland	1				1
India	1	3			1
Indonesia	1				1
Iran	1				

Table I (continued)

Country	No. of Letters to Embassies	No. of Letters to Government Agencies	No. of Letters to Universities and Institutions	No. of Letters to Private Companies and Persons	No. of Responses to Letters Sent
Iraq	1				
Ireland (Eire)	1				1
Israel	1	9	5		4
Italy	1				1
Jamaica	1				1
Japan	1				
Jordan	1				1
Korea	1				1
Kuwait	1				1
Laos	1				
Latvia					
Lebanon	1				
Liechtenstein					
Lithuania					
Luxenbourg	1	5			3
Malawi	1				1
Malaysia	1				1
Malta	1				1
Mexico	1				1
Monaco					
The Sultanate of Muscat and Oman					
Nepal	1				1
Netherlands	1				
New Zealand	1				1
Nicaragua					
Norway	1				1
Pakistan	1				1

Table I (continued)

Country	No. of Letters to Embassies	No. of Letters to Government Agencies	No. of Letters to Universities and Institutions	No. of Letters to Private Companies and Persons	No. of Responses to Letters Sent
Panama	1	2	1		2
Paraguay	1				
Peru	1			1	2
Philippines	1				
Poland	1				1
Portugal and Possessions	1				
Rumania	1				
San Marino					
Saudi Arabia	1				
Singapore					
Spain	1				1
Sweden	1				1
Switzerland	1				
Syrian Arab Republic	1				
Tanzania	1	2			2
Thailand	1				1
Togo	1				
Trinidad and Tobago	1		1		2
Turkey	1				
U.S.S.R.	1				
Uruguay	1				
Venezuela	1				1
Vietnam	1				1
Yemen					
Yugoslavia	1		2		1

3.0 CONDUCTIVITY - GEOLOGY CORRELATION

The factors which affect the electrical conductivity of earth materials are briefly described in an earlier report by Morgan and Maxwell [1965, p. 14, 15]. These factors form a basis for the correlation between geology, climate and electrical conductivity. There are many experimental studies of this relationship appearing in the literature, a number of which are mentioned in the above report. The general ranges of earth conductivity as indicated by Dakhnov [1959] and also by Watt, Mathews, and Maxwell [1963] were in general supported by the collected data on a worldwide basis.

Because of the relationships between conductivity and phase velocity and between conductivity and attenuation rate at VLF, it is much more important to accurately determine conductivities which are below 10^{-3} mho/meter than to accurately determine conductivities which are 10^{-2} mho/meter and greater. A chart showing the effective conductivity at 60 Hz for Precambrian age rocks is presented in Figure 1,Card [1940]. Although this information is not directly applicable to VLF problems, it proved to be very helpful when information was available regarding the overburden material in areas of Precambrian age rocks. Estimates of effective conductivity at VLF can be made using the same techniques described in Appendix A to relate this information to very low frequencies. Other important studies which can be related to VLF problems include the work of Smith-Rose [1934], Boyce [1952], McCollum and Logan [1913], Tagg [1964], Eliassen [1957], and Clark [1966]. These referenced works are readily available and will not be discussed further. The remainder of this section will be devoted to the presentation of geology conductivity correlation tables (Tables II - IX) which were sent by various contributors

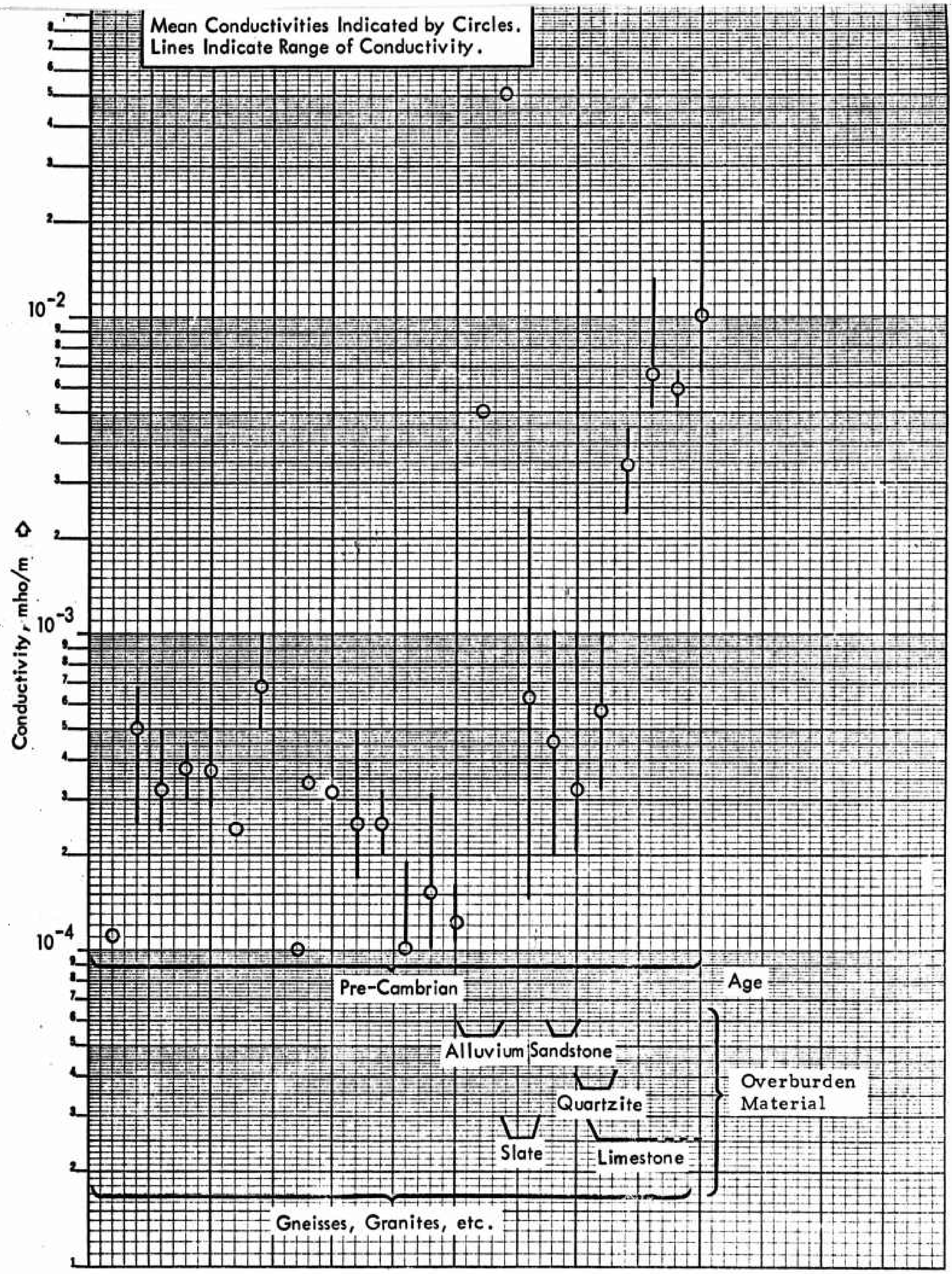


Figure 1 Effective Conductivity at 60 c/s for Pre-Cambrian Age Rocks (from Card, 1940).

throughout the world and which may not be readily available in libraries. It is important to note that this information must be interpreted in light of the regional factors affecting conductivity and also in light of the restricted areas of validity for some of the tables. The information is presented as much as possible in the same form in which it was received. In most instances, there was little additional explanatory material available for these data.

TABLE II

Cyprus

Age	Rock Type	Resistivity in Ohm-meters
Alluvium	Gravels	100 - 1000
	Sand Dunes (above water table)	- 1500
	Silty Sands	30 - 100
	Top Soil	10 - 30
Pleistocene Pliocene	Gravels	20 - 150
	Sands	20 - 150
	Sandstone	20 - 150
	Sandy Marls	12 - 20
	Clays, Marls	2.5 - 12
	Limestone	200 - 1000
Miocene	Reef Limestone (below water table)	30 - 100
	Gypsum	50 - 200
	Marls	2.5 - 8
Upper Cretaceous	Chalks (above water table)	60 - 150
	Chalks (under water table)	10 - 50
	Clays, Marls	1.5 - 5
	Shales	5 - 15
Troodos Pillow Lavas	Upper Pillow Lavas	10 - 50
	Lower Pillow Lava	10 - 40
	Argillic Altered Lavas	5 - 10
	Basal Group	60 - 150
Plutonic Rock		Not available

TABLE III

England

Formation	Resistivity in Ohm-meters
Alluvium	2 - 4
Clay	6 - 10
Coal	20 - 50
Chalk	40 - 50
LS	50 - 60
SS	60 - 100
Igneous Rocks	500 - 1000

TABLE IV

Iceland

Type of Formation	Resistivity in Ohm-meters
Silty Clay with Vegetation	100 - 250
Residual Silty Sand, with Vegetation	500 ± 150
Sandy Soil, without Vegetation	350 ± 100
Sandy, Gravely Soil, without Vegetation	900 ± 150
Gravel, Moist	100 - 400
Stream Gravel	400 - 1000
Pebbles and Sand	1000 - 2500
Moraine	2000 - 7000
Dry Gravel	5000 - 30000
Tertiary Basaltic Rocks, Moist - North and West Iceland	40 - 250
Tertiary Intermediate Rocks, Moist - North and West Iceland	250 - 500
Quaternary Basaltic Rocks Moist - South Iceland	60
Interglacial Basaltic Lavas, Southwest Iceland	300 - 1200
Quaternary Palagonitic Rocks, Southwest Iceland	100 - 200

Table IV (continued)

Type of Formation	Resistivity in Ohm-meters
Postglacial Basaltic Lava, Below Groundwater Level - South Iceland	500 - 3000
Postglacial Basaltic Lava, Above Groundwater Level - South Iceland	3000 - 30000

TABLE V

Israel

Age	Rock Type	Resistivity in Ohm-meters
Quaternary	Muddy Sandstone, Loam, Clays and Mud	2 - 40
	Calcareous Sandstone	< 380
Neogene	Calcareous Shale and Clay, Calcareous Marl (in the west)	5 - 35
	Calcareous and Chalky Sandstone and Sand (in the east)	< 200
Oligocene	Argillaceous Chalk, depending on hardness	40 - 80
Eocene - Upper	Chalk and Marl	8 - 40
- Middle	Marly Chalk with Bedded Flint	20 - 74
	In the Galilee: Marbly Limestone	70 - 200 average: 140
- Lower	Chalk, Flinty Chalk	20 - 74
Paleocene - Danian	Marl and Chalky Marl depending upon amount of marl	2 - 56
Maastrichtian	Bituminous Chalk with Clay and Phosphorite, Glauconite	20 - 36
	Chalk and Bituminous Marl depending on Bituminization	30 - 80
Campanian) Santonian) Senonian	Chalk and Chalky Limestone with Flint	average: 64 < 80

Table V(continued)

Age	Rock Type	Resistivity in Ohm-meters
Turonian	Limestone, some Chalk Limestone	average: 60 60 - 240
Upper Cenomanian	Dolomite	> 100
Middle Cenomanian	Marly Dolomite	average: 100
Northern Israel	Marly Dolomite	
Central Israel	Marly (more) Dolomite	< 1000
Judea Mts.	Mainly Marl	average: 40
Lower Cenomanian	Dolomite	> 100
Basalt, Upper	Depending on Amount of Clays	4 - 40
Basalt, Lower		50 - 160

TABLE VI

Italy

Location	Rock Type	Resistivity in Ohm-meters
Oriental Alps	Calcareous or Dolomitic Calcareous	2000 - 10000
Toscana and Central Appennines	Calcareous	3000 - 10000
Central and Southern Appennines	Clayish	2 - 200
Gargand, Pugliese Peninsula and Trieste	Above the Water level Below the Water level	3000 - 12000 100 - 600

TABLE VII

Lambayeque-Jayanca Area of Peru

Age	Rock Type	Resistivity in Ohm-meters
Soils	Sandy Soil	80 - 200
	Sandy Soil, Cultivated	20 - 50
	Heavy Cultivated Soil	10 - 30
	Highly Saline Soil	1 - 2
Pleistocene Formations	Sand and Gravel (below the water table)	15 - 50
	Clay, Marl, Mudstone, Clayey Sand	4 - 20
Bedrock		50 - 400 and higher

TABLE VIII

Near Village Tiberi, District Thar Parker,

Hyderabad Division - West Pakistan

Lithologic Zones	Resistivity in Ohm-meters
Surface Sandy Soil, with Varying Proportions of Sand and Clay	7 - 30
Dry Sandy	30 - 40
Sandy Zone, Probably Saturated	2 - 30
Fine Sand, Silt and Clay	below 20

TABLE IX

Zambia

Formation	Resistivity in Ohm-meters
Basement	382-1910
Muva	1910 - 3820
Lower Roan Quartzite	1530 - 2860
Lower Roan Shale	286 - 765
Upper Roan	95 - 382
Mwashia	191 - 478
Kakontwe	478 - 2390
Kundelungu	191 - 765
Kalahari	191 - 955
Gabbro and Amphibolite	48 - 191

4.0 TEMPERATURE EFFECTS

Very few measurements of the in situ electrical properties of permafrost are available. One such study which was limited in time and scope is described in the report by Morgan and Maxwell [1965]. These measurements provide a sampling of the in situ conductivity magnitudes and considerable insight into the highly variable nature (and resulting unpredictability) of the electrical characteristics of permafrost regions. It was possible to use these in situ measurements along with laboratory studies of electrical conductivity versus temperature to estimate the electrical properties on a gross regional scale. The accuracy of such estimates is determined to a large extent on: 1) the accuracy of the information relating to the thickness and temperature of permafrost, and 2) the knowledge of the correlation between permafrost characteristics and regional electrical properties. It is emphasized that to date no systematic study of the in situ electrical conductivity of permafrost has been accomplished.

Figure 2 shows the variation in electrical conductivity of rocks and soil with temperature. These data are referenced to laboratory measurements and must be considered in light of the in situ measurements which were made in northern Canada. It appears that the most fruitful approach to the prediction of the electrical properties of a permafrost region at this time is to estimate the regional electrical conductivity assuming there were no permafrost present. A typical or idealized temperature effect curve can then be applied to the specific conductivities (estimated without the temperature considered) and a new electrical model can then be determined. Figure 3 shows such a temperature effect curve based on data such as that presented in Figure 2.

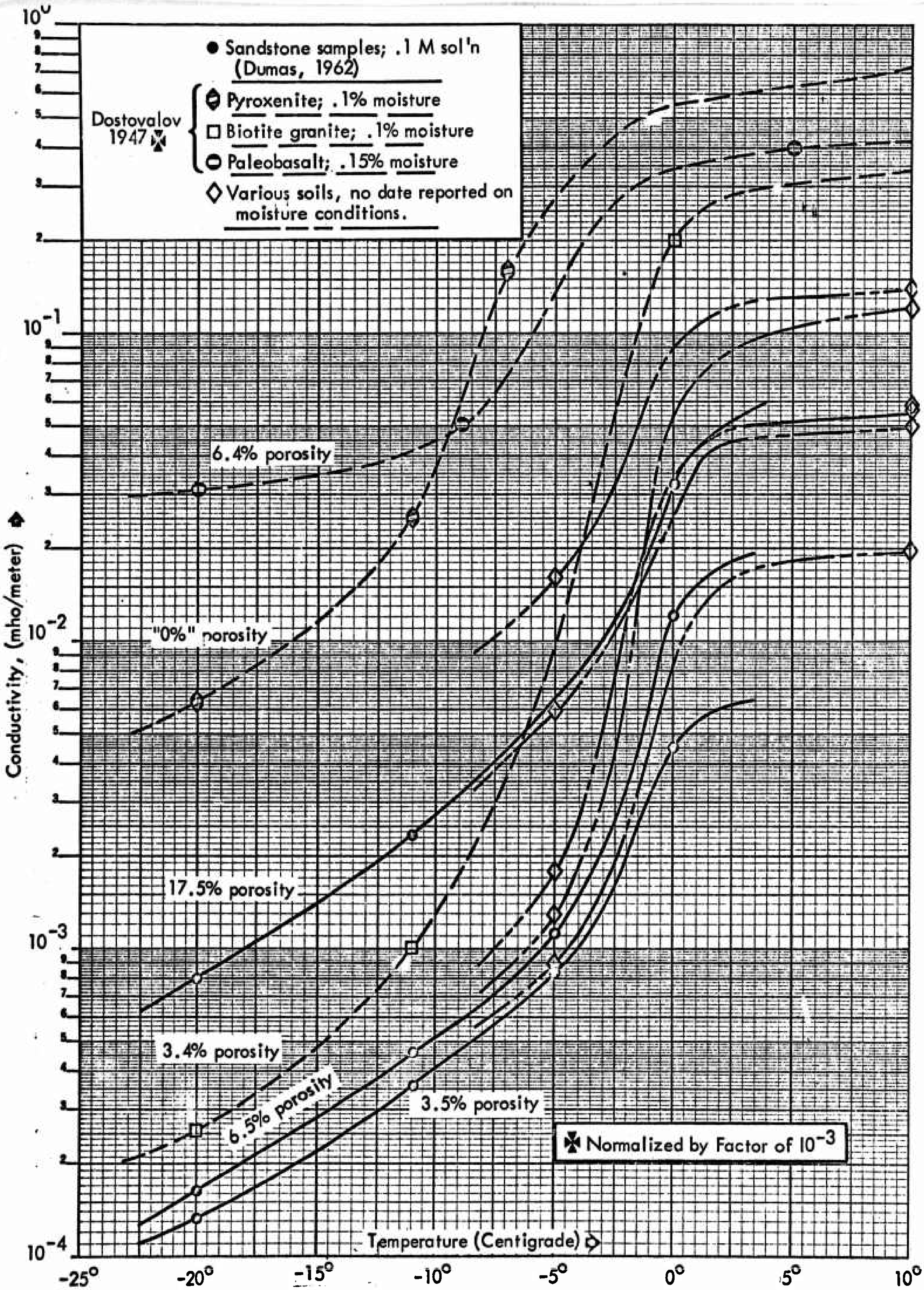


Figure 2 Variation in Electrical Conductivity of Rocks and Soil with Temperature

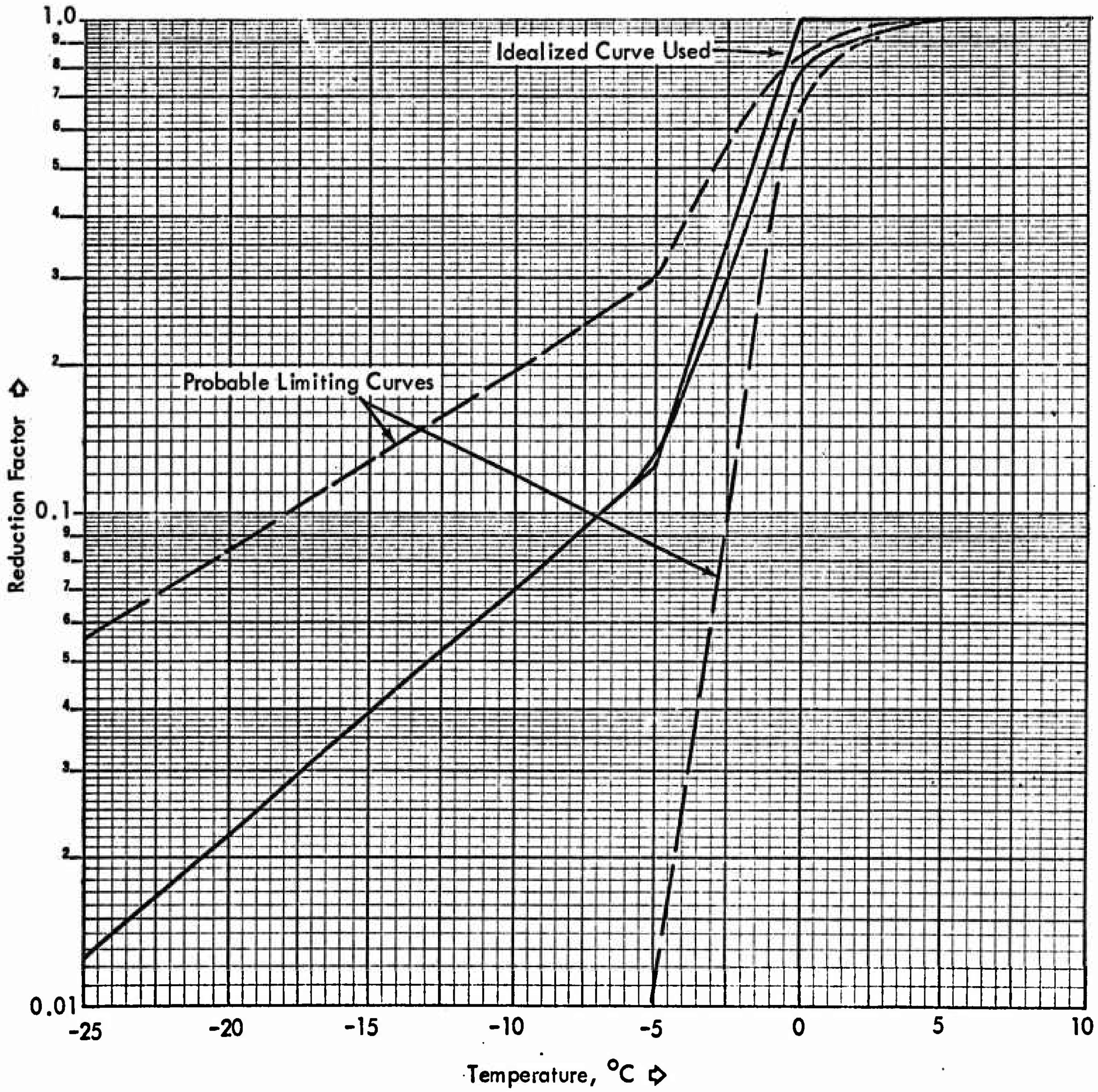


Figure 3 Typical Temperature Effect Showing the Expected Reduction in Electrical Conductivity with Temperature of Pre-Cambrian Igneous and Metamorphic Rocks.

An analysis of the electrical conductivity versus temperature information indicates that the conductivity in rocks decreases by a factor of 10 to 100 with a temperature change from 0° C to a few degrees below. After this initial decrease there is a more gradual decrease in conductivity with temperature. There are, as expected, some exceptions to this in cases of extremely pure infilling water or very dense crystalline rock. Details of conduction mechanisms in frozen earth are not well known at the present time but data indicates that the decrease in rock conductivity depends first upon the purity of the infilling water (the greater the salinity, the less the effect of freezing upon the conductivity) and second, upon the grain size, degree of saturation, and rock material.

Limitations on this method of estimating regional VLF effective conductivities are indicated by the discrepancies between the original map of North America and a revised map based on VLF propagation measurements (See Addendum, pp 22 and 23). Page 21 of the Addendum discusses the comparison of the northern portion of these maps and indicates two significant changes which were required to explain the observed VLF propagation data (this work was done by NRL). It is significant that both of these changes occur in the permafrost region of North America. It is suggested that additional research effort will be required to satisfactorily explain these discrepancies. At least part of the reason for the inaccuracy of the estimates in this area may be the lack of accurate information regarding the depth and temperature of permafrost as well as a lack of accurate geologic information. Areas in the northern portions of the Asian continent appear to be more accurately defined as far as the depth and temperature of permafrost are concerned, and so the corresponding conductivity maps may be more accurate than the map of northern Canada.

5.0 RECOMMENDATIONS

Recommendations for future research may be considered in three parts:

1. Field measurements to check the reliability of the maps and to supplement estimates where the conductivity-geology correlation is not well known,
2. Research program to upgrade and improve this first map,
3. Equipment for VLF wave impedance measurements.

These three parts are considered below.

5.1 Field Measurements

Field measurements to determine effective conductivity values are recommended for the area between Labrador and Hudson Bay, and also for the region just northwest of Hudson Bay. These areas are easily located on the maps, pages 22 and 23 of the Addendum. An experimental value determined from surface based instrumentation would not only allow a more accurate high confidence value of σ_e for this region, but would also provide additional information which would be applicable to the vast permafrost areas in the northern portions of Europe and Asia (see Section 5.3).

It is emphasized that additional geologic field work (reconnaissance) should be done along with the measurements. This will make the extension of the work to other areas possible, and would provide correlation data based on in situ measurements which are presently inadequate.

Since the initiation of downward-looking wave impedance measurements at VLF by Westinghouse personnel in 1963, Farstad [1963], instrumentation,

capable of making fast, reliable measurements, has been considerably improved. On the basis of the simple, reliable and easily portable instruments which are now available, and on the basis of field experience in the Canadian Arctic, the wave impedance method is strongly recommended. A brief description of the equipment and the measurement technique follow. The theory is relatively simple, and is described by Morgan and Maxwell [1965] and Farstad [1963]. It should be noted here that the measured (complex) wave impedance is directly related to the effective conductivity, and therefore represents one of the most direct means of obtaining the effects of a complicated earth on a propagating wave.

5.2 Equipment for VLF Wave Impedance Measurements

Equipment for measuring directly the downward-looking complex electromagnetic impedance of the earth, i.e., wave impedance, at VLF has been developed and can be ready for the measurements recommended above on short notice. The actual measurement involves the comparison of the $\vec{E}$ and $\vec{H}$ fields tangent to the earth's surface. This is accomplished within the instrument by using a familiar null technique: the amplitude and phase of the signal in the $\vec{H}$ field channel is adjusted so that the signal in the $\vec{E}$ field channel is matched. This allows the direct digital readout of the ratio of the magnitudes. Phase information, and spearate field strengths are also obtained. Preliminary laboratory evaluation of the latest system indicates that accuracies on the order of 2% or better may be realized.

The size and weight of the equipment is specifically taylored to a portable one-man operation: dimensions are 9" × 10 1/4" × 17 1/2", and the weight of the main unit is only 16 pounds. The antennas required for a measurement are similarly small and light, and consist of a small shielded air-core loop and a one meter long grounded dipole (the total weight is approximately five pounds for the antennas).

Measurements are rapid, and the stability, reliability and other features important to successful field work are excellent. Westinghouse personnel are highly experienced in the acquisition of this type of field information since 1963, and the present instrumentation system represents the state-of-the-art in the development of this type of field equipment.

5.3 Research Program

It is recommended that a research program be initiated to upgrade and improve this first map in two ways:

1. Improvement of the correlation between known environmental factors and electrical conductivity
2. Continued collection and further analysis of data available through contributors on a worldwide basis.

There are several ways the correlation may be improved with a minimum of effort. The utilization of the field measurements and geologic analysis (as recommended in 5.1) would require only a relatively small additional effort beyond a program which would collect data only for the purpose of determining the effective conductivity of the specific region in which measurements were made. Such an additional effort would allow a much more accurate estimate of the conductivities in the permafrost regions of areas which are not readily accessible for measurements (Northern Europe and Asia).

Additional improvements in the correlation for unfrozen materials can be obtained through a study similar to that described in the report by Morgan and Maxwell [1965]. Information which has become available

since this earlier study includes data on rock descriptions pre-punched on computer cards (similar to the system described in Appendix D of the above referenced report). Only a minimal amount of work would be required to relate measured conductivities (which are also available, but which are not on computer cards) to these rock descriptions.

A research program designed specifically to obtain the desired correlation information would therefore involve a sorting and correlation done almost entirely by computer at a considerable saving in expense and time. Note also the recommendations for this study in the referenced report [Morgan and Maxwell, 1965], with the important distinction that the data mentioned can be obtained at this time which is already on punch cards, and which requires little additional effort prior to the analysis phase of the work.

It is recommended that the data collection and analysis be continued to allow advantage to be taken of the many contacts and sources of measurement data. The willingness of workers to send so much valuable information attests to the wisdom of a continuing effort. It is obviously cheaper to write a letter requesting measurement information than it is to initiate a worldwide measurement program. The notable exception to this general approach includes the permafrost regions, where so little work is being done.

The analysis of the received data should include maps of greater detail than were used for this present project, to allow the consideration of small scale survey data to a greater extent than was possible within the scope of this first map.

REFERENCES

Boyce, C. F. (1952), The Earthing of Telephone Systems with Particular Reference to South Africa, Transactions of the S.A. Institute of Electrical Engineers.

Card, R. H. (1940), Correlation of Earth Resistivity with Geological Structure, Transactions of the AIME, V. 138, pp. 380 - 398.

Clark, S. P., Jr. (1966), Handbook of Physical Constants, Revised Edition, The Geological Society of America, Inc., New York, New York.

Dakhnov, V. N. (1959), Geophysical Well Logging, Quarterly of the Colorado School of Mines, V. 57, No. 2, Translated into English by Dr. G. V. Keller.

Eliassen, K. E. (1957), A Survey of Ground Conductivity and Dielectric Constant in Norway within the Frequency Range 0.2 - 10 Mc/s, Geophysics Publ., 19, No. 11, 1-30.

Farstad, A. J. (1963), Resistivity Measurements by the Audio-Magneto-Telluric Method, DECO Report No. 30-S-2, Contract Nonr 3387(00).

McCollum, B., and K. H. Logan (1913), Electrolytic Corrosion of Iron in Soils, Technologic Papers of the Bureau of Standards, No. 25.

Morgan, R. R. and E. L. Maxwell (1965), Omega Navigational System Conductivity Map, DECO Report 54-F-1, Under Contract NOnr 4107(00).

Smith-Rose, R. L. (1934), Electrical Measurements on Soil with Alternating Currents, Institute of Electrical Engineers Journal, V. 75.

Tagg, G. F. (1964), Earth Resistances, Pitman Publishing Company, New York, New York.

Watt, A. D., F. S. Mathews and E. L. Maxwell (1963), Some Electrical Properties of the Earth's Crust, Procedures of the IEEE, V. 51, No. 6.

BLANK PAGE

APPENDIX A

CALCULATION OF EFFECTIVE CONDUCTIVITY FOR A TWO-LAYER CONDUCTING EARTH

This Appendix describes how the magnitude of effective conductivity over a two-layer conducting earth may be quickly determined by using the curves presented in Figure A-1. These curves are normalized with respect to the thickness and conductivity of the first layer, and are used in conjunction with the skin-depth chart presented in Figure A-2. See Morgan and Maxwell [1965], Appendix A for a more complete discussion of the theory relating to this subject. Other references include the following: Wait [1962], Jackson, Wait and Walters [1962], and Wait [1962a].

To determine the magnitude of the (complex) effective conductivity, σ_e, the following procedure is followed:

1. Determine the ratio σ_2/σ_1, where σ_1 is the specific conductivity of the first (surface) layer, and σ_2 is the specific conductivity of the lower layer.

2. Select the appropriate parametric curve in Figure A-1 which corresponds to the above ratio. Note that the curves are drawn for ratios of 0, 0.0001, 0.001, 0.0045, etc. Ratios are to be interpolated between the values shown in the usual manner.

3. The electrical thickness in "skin depths" is determined next for the first layer. Figure A-2 gives the skin depth, δ, in meters for a given conductivity between 1 mho/meter and

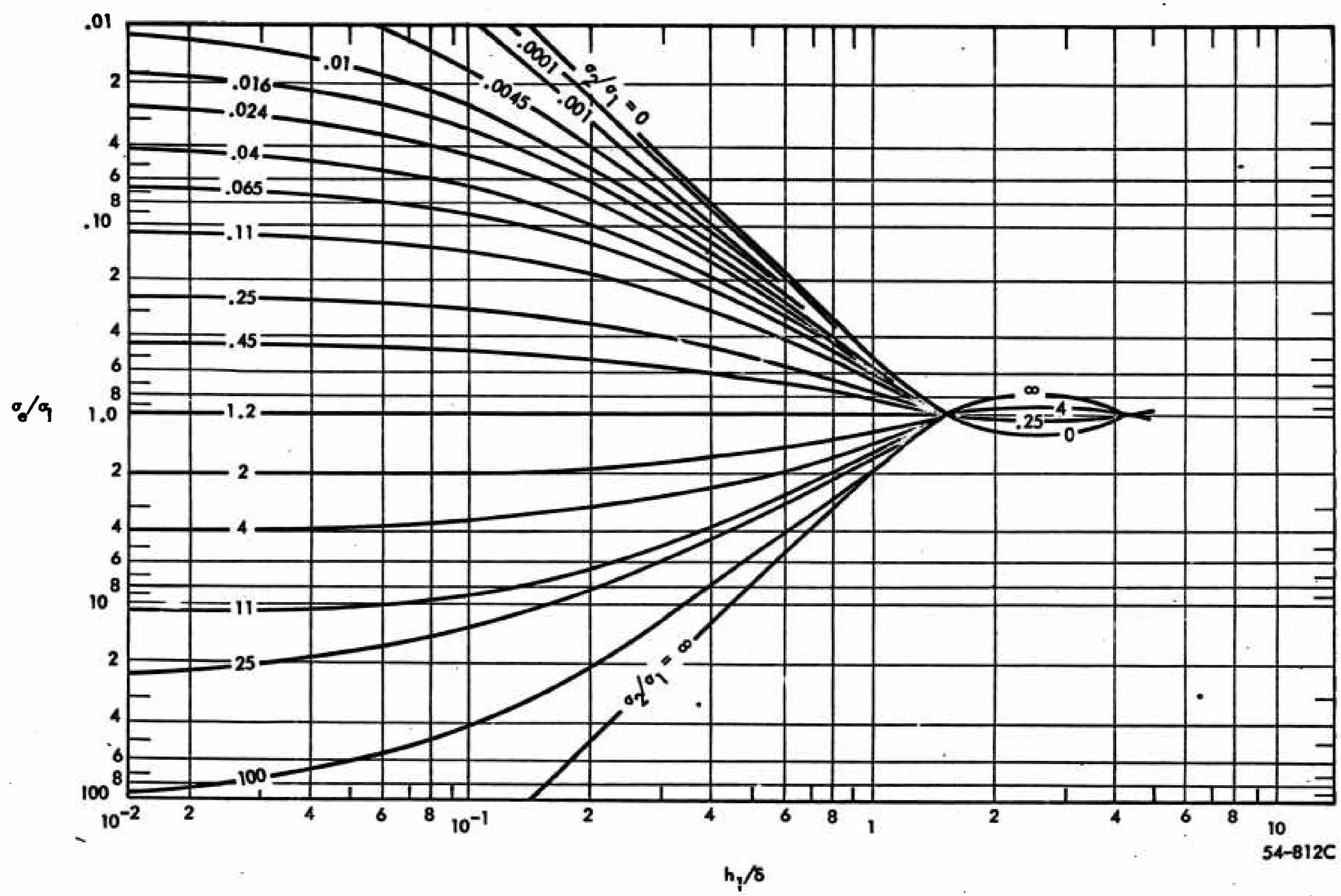


Figure A-1 Nomograph for Determining $|\sigma_e|$, Effective Conductivity, for a Horizontally-Stratified, Two-layer Earth

Skin Depth as a Function of Frequency

$$\delta = \left(\frac{2}{\omega \mu_o \sigma}\right)^{1/2} \left\{ \left(\frac{\omega^2 \epsilon^2}{\sigma^2} + 1 \right) - \frac{\omega \epsilon}{\sigma} \right\}^{-1/2} \text{ or}$$

$$\delta = \frac{1}{\alpha} = \frac{1}{\omega} \left\{ \frac{\mu_o \epsilon}{2} \left[\left(1 + \frac{\sigma^2}{\omega^2 \epsilon^2} \right)^{1/2} - 1 \right] \right\}^{-1/2}.$$

For Homogeneous Material, $\mu_{rel} = 1$

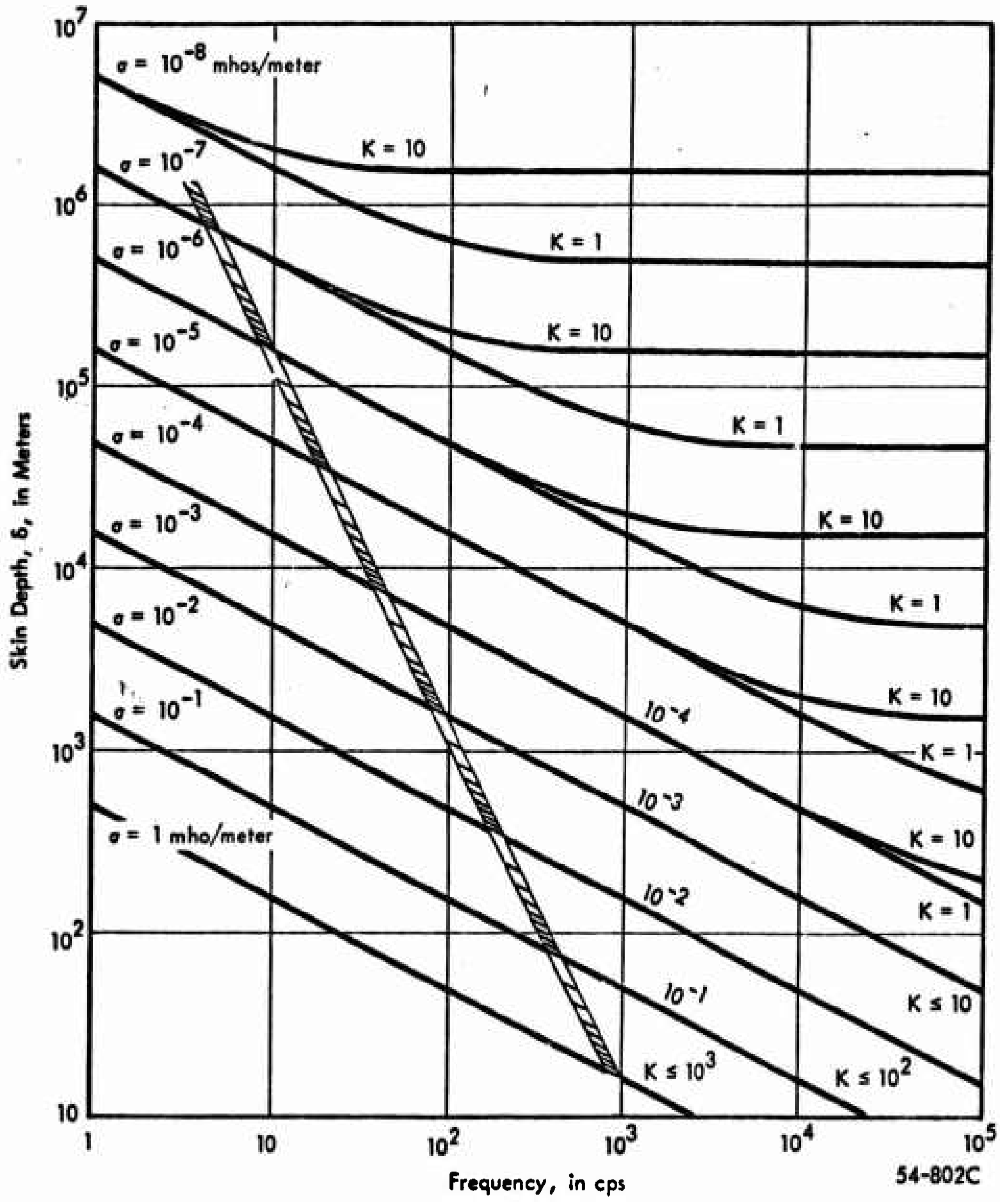


Figure A-2 Skin Depths as Function of the Frequency of Electromagnetic Waves for Various Conductivities and Permittivities, Where $k = \epsilon / \epsilon^o$.

10^{-8} mho/meter. The desired electrical thickness of the first layer is determined simply by dividing the thickness of the layer, h_1, by the skin depth, δ, to give a value of h_1/δ.

4. The effective conductivity can now be determined from Figure A-1 by locating the intersection of the parametric curve, σ_2/σ_1, or the interpolated value, with the h_1/δ value. The value of σ_e/σ_1 is then read from the ordinate, and multiplied by σ_1 to give the appropriate σ_e.

An example may be helpful in understanding the above explanation. Given a two-layer earth with the following data:

σ_1 = 0.1 mho/meter

σ_2 = 0.004 mho/meter (4 millimhos)

h_1 = 1.5 meters

f = 10^4 Hz.

Following the above steps 1 through 3, we determine: $\sigma_2/\sigma_1 = 0.04$, $\delta \doteq 15$ meters, $h_1/\delta = 0.1$. Applying step 4, above, we find that σ_e/σ_1 (from Figure A-1) is 0.07. The effective conductivity is therefore (0.07)(0.1) or .007 mho/meter in magnitude. It is clear that even though the surface layer was 25 times more conducting than the bedrock, the magnitude of the resulting effective conductivity of the combination is not quite twice as conducting as the bedrock alone. This is due to the small electrical thickness of the overburden, at the frequency of interest. Notice the effect of changing the other parameters in this example. If the lower conductivity is

increased so as to increase the ratio σ_2/σ_1, the effect of the conducting overburden will be even less than expected due to the flattening of the curves as one moves from ratios of 0.04 to 0.065 and 0.11.

REFERENCES - APPENDIX A

Jackson, C. M., J. R. Wait, and L. C. Walters, Numerical results for the surface impedance of a stratified conductor, NBS Technical Note No. 143, March 19, 1962.

Morgan, R. R. and E. L. Maxwell, Omega navigational system conductivity map, DECO Report No. 54-F-1, December 1965, ONR Contract NOnr 4107(00) Nr 371-630 dated January 15, 1963.

Wait, J. R., Electromagnetic Waves in Stratified Media, Pergamon Press, 1962.

Wait, J. R., The propagation of electromagnetic waves along the earth's surface, pp. 243-290, in Electromagnetic Waves (edited by R. E. Langer), University of Wisconsin Press, Madison, 1962a.

APPENDIX B

A BIBLIOGRAPHY OF PERMAFROST AND ITS ELECTRICAL PROPERTIES

Permafrost commonly has electrical conductivities of 10^{-3} mho/meter and lower. Because of the importance of distinguishing these low conductivities (as explained in the main text), the occurrence and electrical properties of permafrost were initially studied in some detail to allow the fabrication of the map of North America (Morgan and Maxwell, 1965, Appendix B). Although the scope of the present work did not allow for any major extension of this initial correlation study, a considerable number of references were obtained in a library search, and are tabulated here.

Akimov, A. T., Consistent factors in spatial variation of some physical parameters of permafrost formations in the Bolshezemelskaya tundra; Akademiya Nauk SSR, Institut Merzlotovedeniia, 1961. (In Russian) Bib. On Snow, Ice, and Permafrost, Vol 16, January 1962.

Akimov, A. T., Results of permafrost and geophysical investigations in the eastern part of the Bolshezemelskaya tundra; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, No. 15, pp. 5-46, 1959. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol 15, January 1961.

Ananian, A. A., Specific electric conductivity of frozen ground of natural structure from the Igarka region; Merzlotyne Issledovaniia (Moscow University), No. 1, pp. 208-215, 1961. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963.

Ananian, A. A. and V. P. Dobrovol'skii, Electric conductivity of frozen soils; Geologiia I Geofizika, No. 3, pp. 96-103, 1961. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 16, January 1962, pp. 46-47.

Ananian, A. A. and V. P. Dobroval'skii, Specific electric conductivity of frozen ground of natural structure from the Salekhard region; Merzlotyne Issledovaniia (Moscow University), No. 1. pp. 216-226, 1961. (In Russian). Bib. On Snow, Ice and Permafrost, Vol. 17, June 1963.

Ananyon, A. A., Dependence of the electrical conductivity of frozen rocks on saturation; Akademiya Nauk SSSR, Izvestiya, Seriya Geofizicheskaya, No. 12, pp. 1504-1509, 1958. (In Russian). Geophysical Abstracts, No. 176-179, January-December 1959, pp. 173-174.

Barnes, D. F. and G. R. MacCarthy, Tests of geophysical prospecting techniques in areas of sporadic permafrost in interior Alaska; Bulletin of the Geologic Society of America, No. 67, p. 1805, Dec. 1956. Bib on Snow, Ice and Permafrost, Vol. 13, January 1959, p. 105.

Black, R. F., Permafrost - Review; Bulletin of the Geological Society of America. 65, No. 9, pp. 839-855, September 1954. The Eng. Index, 1954, p. 999.

Bodman, G. B. and P. R. Day, Freezing Points of California soils and their extracted clays; Soil Science, 55, 1943.

Borovinskii, B. A., Electrical survey on moraines of the Malaya Almatinka Glaciers; Alma-Ata, Tzd-Vo Akad. Nauk Zazakhskot SSR, pp. 113-135, 1961. (In Russian, English summary). Bib. on Snow, Ice, and Permafrost, Vol. 19, June 1965.

Borovinsky, B. A., On the question of the researches of the glaciers by the methods of the electrical prospect.; Publ. No. 54, Intern. Assoc. Sci. Hydrol. Gentbrugge, Belgium, 1961. Bib. on Snow, Ice, and Permafrost, Vol. 16, January 1962.

Brant, A. A., The role of geophysical methods in modern exploration programs; Engineering and Mining Journal, 156, No. 3A, pp. 25-32, 1955. Geoph. Abstracts, No. 1033, 1955, p. 132.

Brewer, Max C., Some results of geothermal investigations of permafrost in northern Alaska; American Geophysical Union, Transactions, 39, No. 1, pp. 19-26, February, 1958. Met. and Geoastro. Ab's, Vol. 10, Pt. 1, 1959, p. 238.

Brown, R. J. E., A review of permafrost investigations in Canada; Canadian Geographer, 6, No. 3-4, pp. 162-165, Winter 1962.

Brown, R. J. E., The distribution of permafrost and its relation to air temperature in Canada and the U. S. S. R.; Arctic, 13, No. 3, pp. 163-177, September 1960.

Brown, R. J. E. and G. H. Johnston, Permafrost and related engineering problems; Endeavor, 23, No. 89, pp. 66-72, 1964.

Brown, W. G., Difficulties associated with predicting depth of freeze or thaw; Canadian Geotechnical Journal, 1, No. 4, pp. 215-226, November 1964.

Bush, B. O. and S. D. Schwarz, Seismic refraction and electrical resistivity measurements over frozen ground; Proceedings of the Canadian Regional Permafrost Conference, 1964. National Research Council of Canada Associate Committee on Soil and Snow Mechanics Technical Memoir No. 86, pp. 32-37, 1965. Ab.'s of N. Am. Geol., July, 1966, p. 709.

Cagniard, L., Graph for electrical soundings in ice; Ann. Geophys, 15, No. 4, pp. 561-563, Oct.-Dec. 1959. (In French) Bib. on Snow, Ice, and Permafrost, Vol. 14, January 1960.

Cass, J. R., Subsurface explorations in permafrost areas, Proceedings of the American Society of Civil Engineers, 85, pp. 31-41, October 1959. App. Sc. and Tech. I., 1960, p. 1242.

Cook, John C., RF electrical properties of salty ice and frozen earth, Journal of Geophysical Research, 65, No. 6, pp. 1767-1771, June 1960. Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

Dobretsov, V. B. and Yu. I, Protasov, Investigation of the electrical resistivity of rocks and minerals at low temperatures; Akademiya Nauk SSSR, Institut Fiziki Zemli, Trudy, No. 4, pp. 102-103, 1965. (In Russian). Geoph. Abstracts, No. 238, Nov. 1966, p. 1023.

Dobrovol'skii, V. P., Certain characteristics of the interpretation of electrical sounding curves obtained during investigations of permafrost thickness; Geolog.-Geograf. Nauki, No. 2, pp. 127-133, 1959. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

Dobrovol'skii, V. P., Electrical anisotropy of frozen ground; Merziotyne Tssledovaniia, (Moscow University), 2, pp. 157-164, 1961. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June, 1963.

Dostovalov, B. N., Electrical characteristics of frozen rocks; Proceedings of the V. S. O. Breechev Permafrost Institute, Vol. V, Electrometry and Ondometry of Frozen Rock Strata, (In Russian).

Dostovalov, B. N., Electrical prospecting of permafrost with the resistance method; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, 2, pp. 172-176, 1956. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 14, January 1960, p. 13.

Dostovalov, B. N., Permafrost investigations by the resistance method along the lower reaches of the Indigirka River; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, 15, pp. 81-112, 1959. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

Dostovalov, B. N., Permafrost survey by the resistance method in Northwestern Siberia; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, 15, pp. 47-80, 1959. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

Drew, J. V., et al, Rate and depth of thaw in arctic soils; American Geophysical Union, Transactions, 39, No. 4, pp. 697-707, August 1958. The Eng. Index, 1958, pp. 1157-1158.

Dukhin, I. Ye and V. N. Polyakov, Some results of the application of electrometric methods to the determination of the lower surface of frozen rocks; Akademiya Nauk SSSR, Institut Merzlotovedeniya, Trudy, 4, pp. 71-77, 1964. (In Russian). Geoph. Abstracts, No. 228, January 1966, p. 27.

Dumas, Michel, Electrical resistivity and dielectric constant of frozen rocks; Thesis for MSc, Colorado School of Mines, Golden, Colorado, 1962.

Eliassen, K. E., A survey of ground conductivity and dielectric constant in Norway within the frequency range 0, 2-10 Mc/s; Geofys. Publikasjoner, 19, No. 11, pp. 1-30, 1957. Bib. on Snow, Ice, and Permafrost, Vol. 13, January 1959.

Evans, S., Radio techniques for the measurement of ice thickness, Polar Record, 11, No. 75, p. 795, September 1963. Bib. on Snow, Ice, and Permafrost, Vol. 18, June 1964.

Frolov, A. D., Use of the fields of radio broadcasting stations to map the contacts of permafrost layers; Merzlotnye Issledovaniia. (Moscow University), 1, pp. 227-235, 1961. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963.

Greenland Research Program - 1959. (Snow, Ice, and Permafrost Research Establishment). Washington, D. C.; Government Printing Office, 1959. U. S. Gov. Pub's, Monthly Catalog, Oct. 1959, p. 47.

Hatherton, T., Electrical resistivity of frozen earth; Journal of Geophysical Research, 65, No. 9, pp. 3023-3024, September 1960. Geoscience Abstracts, Vol. 3, No. 1, January 1961, p. 25.

Hessler, V. P. and A. R. Franzke, Earth-potential electrodes in permafrost and tundra; Arctic, 11, No. 4, pp. 211-217, 1958. Geoscience Abstracts, Vol. 2, No. 1, January 1960, p. 32.

Higgs, P. J., An investigation of earthing resistances; Journal of the Institute of Electrical Engineers, 68, No. 402, pp. 736-750, June 1930. The Eng. Index, A-I, 1930, p. 668.

Hochstein, Manfred, Electrical measurements on the Greenland ice cap; Meddelelser Om Grønland, 177, No. 3, pp. 60-99, 1965. (English Abstract). Abstracts of N. Am. Geol., December 1966, p. 1316.

Hochstein, M., Electrical resistivity measurements on ice sheets; Journal of Glaciology, 6, No. 47, pp. 623-634, June 1967.

Hoekstra, P. and E. Chamberlain, Soil Science Electro-Osmosis in Frozen Soil; Nature, 203, No. 4952, pp. 1406-1407, September 26, 1964. Bib. on Snow, Ice, and Permafrost, Vol. 19, June, 1965, pp. 129-130.

Hopkins, D. M., et al, Permafrost and ground water in Alaska; (U. S. Geological Survey, Professional Paper No. 264-F). Washington, D. C., U. S. Gov't. Printing Office, 1955. The Eng. Index, 1955, p. 974.

I'Akupov, V. S., Determination of the thickness of recent loose deposits by the vertical electrical sounding method in regions of low-temperature permafrost; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, 15, pp. 144-183, 1959. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

I'Akupov, V. S., Potentialities of geoelectric exploration in permafrost regions; Razvedka I Okhrana Nedr., 26, No. 10, pp. 29-32, October 1960. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963.

International Conference on Permafrost, Lafayette, Indiana; Civil Engineering, 34, p. 61, January 1964. App. Sc. and Tech. I., 1964, p. 1180.

Johnston, G. H., R. J. E. Brown, and D. N. Pickersgill, Permafrost investigations at Thompson, Manitoba terrain studies; Tech. Paper No. 158 of the Division of Building Research, Ottawa, Canada, 1963.

Kashprovskiy, V. Ye, Correlation between the electrical conductivity of soils and their physical-chemical properties; Geomagnetism and Aeronomy, 3, No. 5, pp. 771-775, 1963.

Kashprovskiy, V. Ye., Local conductivities of soils and their distribution over the territory of the USSR; Geomagnetism and Aeronomy, 3, No. 2, pp. 240-248, 1963.

Kashprovskiy, V. Ye., Specific features of propagation of ground waves in permafrost zone, USSR; Geomagnetizm I Aeronomiya. 5, No. 4, July-August 1965. U. S. Gov't. Pub's; Monthly Catalog, November 1965, p. 79.

Kashprovskiy, V. Ye, and F. A. Kuzubov, Soil relief irregularities and their influence on the propagation of surface waves; Geomagnetism and Aeronomy, 3, No. 3, pp. 427-435, 1963.

Keller, George V., Electrical properties of rocks and minerals; Section 26 in Handbook of Physical Constants, Revised Edition. Geologic Society of America Memoir No. 97, pp. 553-577, 1966. Geoph. Abstracts, No. 244, May 1967, p. 449.

Keller, G. V. and F. C. Frischknecht, Electrical Methods in Geophysical Prospecting; Pergamon Press, New York, 1966. Cumulative Book I, Aug.-Dec. 1966, p. 242.

Keller, G. V. and F. C. Frischknecht, Electrical resistivity studies on the Athabasca Glacier, Alberta, Canada; Journal of Research of the National Bureau of Standards, 64, No. 5, pp. 438-448, September-October 1960. Met. and Geoastro. Abstracts, Vol. 11, Pt. 2, 1960, p. 1899.

Keller, G. V., and F. C. Frischknecht, Induction and galvanic resistivity studies on the Athabasca Glacier, Alberta, Canada; Geology of the Arctic, 2, pp. 809-832. Bib. on Snow, Ice, and Permafrost, Vol. 16, January 1962.

Konstantinova, G. S., Determination of soil freezing by the electrical resistance method; Moscow Universitet, pp. 184-190, Moscow, 1962. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963.

Korkina, R. I., Electrical resistance of frozen sedimentary bedrock associated with phase features of their formation; Materialy K Osnovam Ucheniia O Merzlykh Zonakh Zemnoi Kory., 4, pp. 46-49, 1958. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961.

Kozel, J., Dependence of specific resistivity of sedimentary rocks on temperature; Moscov. Inst. Neftekhim. I. Gazov. Promyshlennosti Trudy, No. 56, pp. 23-28, 1966. (In Russian). Geoph. Abstracts, No. 239, December 1966, p. 1147.

Lafargue, M. and R. Millecamps, Electromagnetic properties of glacier ice; Compt. Rend., 247, No. 12, pp. 884-886, September 22, 1958. (In French). Bib. on Snow, Ice, and Permafrost, Vol. 14, January 1960.

Lapina, I. Ye, Soviet investigations in the Antarctic (All-Union Symposium); Akademiya Nauk SSSR Vestnik, No. 7, pp. 95-97, 1966. (In Russian) Geoph. Abstracts, No. 243, April 1967, p. 338.

Leget, R. F., Permafrost research in northern Canada; Nature, 178, No. 4536, pp. 716-717, October 6, 1956. Bib. of N. Am. Geol., No. 1075, 1956, p. 149.

Legget, R. F., H. B. Dickens, and R. J. E. Brown, Permafrost investigations in Canada; Geology of the Arctic. 2, pp. 956-969, 1961, Bib. of N. Am. Geol., No. 1197, 1961, p. 213.

Leshchikov, F. N., Investigation of the seasonal freezing and thawing of ground by means of vertical electric sounding; Geologiia I. Geofizika, No. 1, pp. 143-146, 1962. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963.

Lovell, Charles W., Jr., Review of Certain Properties and Problems of Frozen Ground, Including Permafrost. (U.S. Army Corps of Engineers, SIPRE Report No. 9). Washington, D.C., U.S. Gov't. Printing Office, 1953. Bib. of N. Am. Geol., No. 1035, 1952-1953, p. 211.

MacCarthy, Gerald R., Natural earth potential anomalies near Point Barrow, Alaska; American Geophysical Union Transactions, 36, No. 3, p. 519, June 1955. Bib. of N. Am. Geol., No. 1065, 1955, p. 162.

Maksimenko, N. N., Electrophysical characteristics of permafrost grounds; Elfktrichestvo, No. 3, pp. 71-74, 1963. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 18, June 1964.

McCollum, B., and Logan, Electrolytic corrosion of iron in soils; Technologic Paper No. 25 of National Bureau of Standards, June 12, 1913.

Mendoza, E. and J. G. Thomas, Electrical resistance of gold, silver, and copper at low temperatures; Philosophical Magazine, 42, No. 326, pp. 291-303, March 1951. The Eng. Index, 1951, p. 374.

Meyer, A. U. and H. Roethlisberger, Electrical D-C resistivity measurements on glacier ice near Thule, Greenland. (U.S. Army Cold Regions Research and Engineering Labratory, Technical Report No. 87). Washington, D.C. U.S. Government Printing Office, 1962. Bib. on Snow, Ice, and Permafrost, Vol. 17, June 1963, p. 203.

Muller, Siemon William, Permafrost or Permanently Frozen Ground and Related Engineering Problems. Ann Arbor: The Edwards Brothers Company, 1947. Cumulative Book I., 1943-1948, p. 1559.

Nesterenko, I. P., and N. A. Gorelikov, Detection of frozen lenses in fill using the methods of electric exploration; Transportnoe Stroitel'stvo. 10, No. 1, pp. 39-40, January 1960. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 16, January 1962.

Nesterov, M. A. and L. Ya. Nesterov, Electrical conductivity of rocks at temperatures below zero; Uses - Nauch - Issled. Geol. Inst. Mater., Geofiz., 11, 1947. (In Russian).

Nozhevnikov, V. E., Grounding of electrical installations under permafrost conditions; Institut Merzlotovedeniya, Akademiya Nauk SSSR, pp. 172-176, 1959. Bib. on Snow, Ice, and Permafrost, Vol. 14, January 1960.

Østrem, Gunnar, Laboratory measurements of the resistivity of ice; Journal of Glaciology, 6, No. 47, pp. 643, June 1967.

Principles of Geocryology (Permafrost Studies), Part I. Academy of Sciences of the U. S. S. R., V. A. Obruchev Institute of Permafrost Studies, Moscow, 1959. (T. T. of Canadian National Research Council).

Queille-Lefevre, C. and Bauer, and Girard, First attempt at measuring the thickness of a glacier electrically; Ann. Geophys, 15, No. 4, pp. 564-567, October-December 1959. Bib. on Snow, Ice, and Permafrost, Vol. 14, January 1960.

Ray, Louis Lamy, Permafrost; Arctic, 4, No. 3, pp. 196-203, December 1951. Bib. of N. Am. Geol., No. 1025, 1951, p. 151.

Robertson, E. I. and W. J. P. MacDonald, Electrical resistivity and ground temperature at Scott Base, Antarctica; New Zealand Journal of Geology and Geophysics, 5, No. 5, pp. 797-809, December 1962. Bib. on Snow, Ice, and Permafrost, Vol. 18, June 1964, p. 172.

Rothlisberger, Hans, Electrical resistivity measurements and soundings on glaciers; Introductory remarks; Journal of Glaciology, 6, No. 47, pp. 599-606, June 1967.

Rothlisberger, Hans, and Kurt Vogtli, Recent D. C. resistivity soundings on Swiss glaciers; Journal of Glaciology, 6, No. 47, pp. 607-622, June 1967.

Rudakov, V. N. and V. V. Bogorodskii, Problem of measuring glacier thickness by electromagnetic methods; Zhurnal Tekhnicheskot Fiziki. 30, No. 1, pp. 82-89, January 1960. (In Russian). Bib. on Snow, Ice, and Permafrost, Vol. 15, January 1961, p. 148.

Semenov, A. S., Influence of various factors on magnitude of resistivity of friable soils at below zero temperatures; Lem. Gorn. Inst., 1937. (In Russian).

Smith-Rose, R. L., Electrical measurements on soil with alternating currents; Inst. Elec. Engineers Journal, 75, 1934.

Sokolov, S. A., Reduction of ground resistance in rocky locations and permafrost areas; Elcktrosvyaz, 13, No. 6, pp. 65-70, June 1959. (In Russian). The Eng. Index, 1959, p. 367.

Stozharov, N. B., Use of electrical surveying methods under permafrost conditions; Geofizicheskie Metody Razvedki V Arktike, 132, No. 4, pp. 204-214, 1962. (In Russian). Geophysical Abstracts, No. 199, August 1963, p. 686.

Sumgin, M. I. and A. A. Petrovsky, The importance of electrical methods for the study of permanently frozen ground; Akademiya Nauk SSSR, Institut Merzlotovedeniya Trudy, 5, pp. 15-17, 1947. (In Russian). Geoph. Abstracts, No. 133, April-June 1948, p. 130.

Tiutiunov, Ivan Alekseevich, An Introduction to the Theory of the Formation of Frozen Rocks; New York, The MacMillan Company, 1964. Cumulative Book Index, January 1963-December 1964, V. 1, A-K, p. 1097.

Vogtli, Kurt, D. C. resistivity soundings on Devon Island, N. W. T., Canada; Journal of Glaciology, 6, No. 47, pp. 635-642, June 1967.

Watt, A. D. and E. L. Maxwell, Measured electrical properties of snow and glacial ice; Journal of Research of the National Bureau of Standards, 64, No. 4, pp. 357-363, July-August 1960. Met. and Geoastro. Abstracts, Vol. 11, Pt. 1, 1960, p. 1185.

Weiner, L., P. Chiotti, and H. A. Wilhelm, Temperature Dependence of Electrical Resistivity of Metals; (U. S. Atomic Energy Commission, Bulletin). Washington, D. C., U. S. Government Printing Office, 1953. U. S. Gov't. Pub.'s, Monthly Catalog, December 1953, p. 17.

Zuyev, G. N., Study of seasonal variations of electrical conductivity of unconsolidated deposits in place with stationary vertical electrical sounding set-up in a permafrost region; Byulleten' Nauchno-Tekhnicheskov Informatsii, 1, No. 45, pp. 51-57, 1963. (In Russian). Geoph. Abstracts, No. 216, January 1965, pp. 26-27.

BLANK PAGE

APPENDIX C

LIST OF CONTRIBUTORS

This Appendix includes a list of persons and organizations who sent and aided in the collection of helpful information relating to the Worldwide VLF Effective Conductivity Map. Nearly all the information sent was of some use in the fabrication of the Map. It was beyond the scope of this present research to analyze in detail some of the many surveys of small areas, or areas which were by nature "anomalous" in the context of regional average conductivities. A similar comment applies to some surveys of 1 MHz field strength versus distance. In the latter cases, the information when reduced would be similar to the broadcast frequency maps (see comments in the Addendum, p. 1). Information of the above nature is gratefully acknowledged, however, and if future research programs warrant a more detailed analysis (or an effective conductivity map on a smaller scale) the above contributions will be carefully studied.

There are some contributors who sent information through the U. S. embassies. Because of this additional handling of the information, there may be omitted from the list some of these contributors. If such an omission has occurred for this or any other reason, it is sincerely regretted. The listing is by name. Grateful acknowledgement is made to all those in this list, and especially to all of the U. S. embassies who contributed a major part in the collection of the data (the embassies are not listed).

Dr. Ebun Ade-Hall
University of Ife
Ibadan, Nigeria

Mr. L. Alexandrenne
Republic of Senegal Service of Mines and Geology
Senegal

American Independent Oil Company
Kuwait and Saudi Arabia

Dr. Jose E. Arce
Geologist-Geophysicist
Lima, Peru

Argentine Government Agencies
Buenos Aires, Argentina

Austrian Broadcasting Company
Austria

Mr. Sveinbjorn Bjornsson
Department of Natural Heat
Reykjavik, Iceland

Mr. Blackston, Jr.
American Embassy
Amman, Jordan

Bureau of Mineral Resources
Geological Survey
Government of Pakistan
Pakistan

Compagnie Luxembourgeoise de Telediffusion
Luxembourg, Luxembourg

Department of Research and Investigation
National Resources Authority
Jordan

Mr. Julian A. Fernandez
Instituto Nacional Geologia y Mineria
Buenos Aires, Argentina

The Geological Survey Department
Lobatsi, Bechunaland

Geological Survey of Greenland
Greenland

Dr. A. Ginzburg, Scientific Director
The Institute for Petroleum Research and Geophysics
Azor, Israel

Dr. Frank Hadsel
Colorado School of Mines
Golden, Colorado

Mr. D. A. Herrera
Shell Trinidad, Ltd.
Trinidad

Mr. J. P. Huie
Nigerian Gulf Oil Company
Lagos, Nigeria

Mr. Paek O. Hyon, Director
Office of Radio Regulatory of the Ministry of Communication
Seoul, Korea

Institute of Geophysics
Tehran University
Tehran

Instituto Geografico y Catastral
Spain

Mr. R. S. Jackson
Water Development Department
Ministry of Natural Resources
Nairobi, Kenya

Mr. C.M.H. Jennings
Geological Survey Department
Lobatsi, Botswana

Dr. J. Kaufmann
Schweizerische Post-, Telephon- und Telegraphenbetriebe
Zurich, Switzerland

Dr. G. V. Keller
Colorado School of Mines
Golden, Colorado

Ing. Alforiso Campins Leal, Director General
Direccion General de Mineria y Hydro Carburos
Guatemala, Guatemala

Mr. J. A. McNamara
Australian Broadcasting Control Board
Melbourne, Australia

Ministry of Communications
Government of the Republic of China

Ministry of Communications and Works
Kingston, Jamaica

Mr. F. Mosetti
Osservatorio Geofisico
Trieste

New Zealand Department of Scientific and Industrial Research
Geophysics Division
New Zealand

Andrej Nowinski
Geofizika
Zagreb, Yugoslavia

Dr. David P. Rehruss
Geological Survey of West Malaysia and Department of Agriculture
Kuala Lumpur, Malaysia

RST Technical Services, Ltd.
Geologic Research Unit
Zambia, Africa

Dr. D. P. Schlick
Pakistan

Mr. Enrique Silgado
Consulting Geologist
Lima, Peru

Tahal (Water Planning), Ltd.
Lima, Peru

Dr. A. Tarczy-Hornoch
Magyar Tudomanyos Akademia
Sopron, Hungary

Technical University of Denmark
Copenhagen, Denmark

University of the West Indies
St. Augustine, Trinidad

Mr. Francisco de Vasconcelos Guimaraes
Direccao Provincial dos Servicos de Geologia e Minas
Luanda, Angola

Mr. R. W. Vice
South African Council for Scientific and Industrial Research
South Africa

Dr. John D. Whittingham
Geological Survey and Mines Department
Swaziland, Africa

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Westinghouse Electric Corporation	2a. REPORT SECURITY CLASSIFICATION Unclassified
	2b. GROUP

3. REPORT TITLE

Preparation of a Worldwide VLF Effective Conductivity Map

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Morgan, Robert R.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 March 1968	49	11

8a. CONTRACT OR GRANT NO. N00014-67-C-0274	9a. ORIGINATOR'S REPORT NUMBER(S) 80133F-2
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	none

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Department of the Navy

13. ABSTRACT

A map showing effective electrical earth conductivity values for a propagating wave at VLF (10 kHz to 30 kHz) has been prepared for the major land areas of the world. Land area conductivity determinations were in most cases based upon known geological and climatological information. Actual conductivity data was collected where possible to aid in determining regional effective conductivity values, but the correlation between geology (and other known factors), and conductivity was used in estimating conductivity for the majority of the land areas.

The conductivity data are overprinted on seven 7 X 22 inch base maps, which are separate from this report. Effective conductivity values are designated by numbers from 1 to 10 referenced to a legend on each sheet. Page size maps showing a confidence factor and a variability factor are included in these reports.

A measurement program to establish the reliability of the map and to supplement estimates where the geology-conductivity correlation is not well known is recommended. A research program is also suggested to upgrade and improve the maps.

DD FORM 1 JAN 64 1473

Security Classification

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Effective Electrical Earth Conductivity Correlation Between Geology and Conductivity VLF Effective Conductivity Maps						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification

80133F-1

Submitted to: Office of Naval Research
Department of the Navy
Washington, D. C. 20360
Under contract N00014-67-C-0274

15 January 1968

Robert R. Morgan

ADDENDUM
WORLD-WIDE
VLF EFFECTIVE-CONDUCTIVITY
MAP

Westinghouse Electric Corporation
Environmental Science and Technology Department

ABSTRACT

A map showing effective electrical earth conductivity values for a propagating wave at VLF (10 kHz to 30 kHz) has been prepared for the major land areas of the world. Land area conductivity determinations were in most cases based upon known geological and climatological information. Actual conductivity data was collected where possible to aid in determining regional effective conductivity values, but the correlation between geology (and other known factors), and conductivity was used in estimating conductivity for the majority of the land areas.

The conductivity data are overprinted on seven 17 × 22 inch base maps. Effective conductivity values are designated by numbers from 1 to 10 referenced to a legend on each sheet. Separate page-size maps showing a confidence factor and a variability factor are included in the accompanying report.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

WORLD-WIDE VLF EFFECTIVE-CONDUCTIVITY MAP

1.0 INTRODUCTION

A map showing effective electrical conductivity of the earth at very low frequencies (10 kHz to 30 kHz) has been prepared to aid in radio propagation and navigational studies. Values of conductivity were determined for land areas whose boundaries are in most cases based upon climatological, pedological, physiographical, and geological information. Data was collected to aid in establishing regional effective-conductivity values. It was necessary, however, to rely on the correlation between geology and other known environmental factors and conductivity for the majority of the land areas [1].

It is noteworthy that there is considerable difference between effective-conductivity maps for use at broadcast frequencies (1 MHz) and the VLF map: these differences are due primarily to the greater depth of penetration of the VLF energy. Earth materials to depths of over 50 meters must be considered for conductivities on the order of 10^{-2} mho/meter, and greater depths of penetration are involved for lower conductivities.

Because of the relationships between conductivity and phase velocity, and between conductivity and attenuation rate, it is much more important to accurately determine conductivities which are below 10^{-3} mho/meter than to accurately determine conductivities which are 10^{-2} mho/meter and greater, hence, the lack of detail on the maps for this latter conductivity range. Materials which fall into the lower, more

important range include geologically old, crystalline rocks. Areas where permafrost occurs, and areas with ice caps (Greenland and the Antarctic) are similarly important. Measurements were made in permafrost areas of the Canadian Shield during an earlier program which produced the conductivity map of North America to help define the effect of freezing on the in situ electrical properties of the rocks [2].

The author would like to acknowledge the assistance of Mr. Gary Aho, during the summer of 1967, who shared a large part of the responsibility for the project during that time. The author is indebted to the many scientists and research organizations who sent hundreds of replies to requests for electrical conductivity data. Of particular help in this data collection effort were the United States Embassies throughout the world. Plans are to publish additional material which can include a list of contributors. It is hoped that contributors will continue to send data as it becomes available, and that future editions of the map will therefore be of increased usefulness to the scientific community throughout the world.

2.0 DESCRIPTION AND USE OF MAP

The conductivity map is overprinted on seven 17 × 22 inch base maps supplied by Bonn Cartographic Corporation of Salt Lake City, Utah. The effective-conductivity values are designated by numbers 1 to 10, referenced to a legend on each sheet.

Since little appropriate VLF data exists on a world-wide basis, it is not possible to evaluate directly the accuracy of the entire map. As an alternative, two factors directly related to the reported values are presented. The Confidence Factor refers to the quality, quantity and type of information which determined the regional conductivity values. The Variability Factor indicates the amount by which local values of conductivity can be expected to vary from the regional average.

The above two factors are seen to be independent, and are presented separately for each sheet of the map in Figures 1 through 7. These factors are distinguished as follows:

Confidence Factor

Highest Confidence: Correlation based on sound geologic and conductivity data. These values are not expected to change appreciably from the reported values.

Moderate Confidence: Some data available. Geology-conductivity correlation believed to be reliable. These values will probably not need to be revised by more than one level (one half decade).

Limited Confidence: Geology-conductivity correlation not well known. Some data may be available, but it is limited in quantity or quality. These values may change as data becomes available.

Figure 1A Confidence Factor for North America

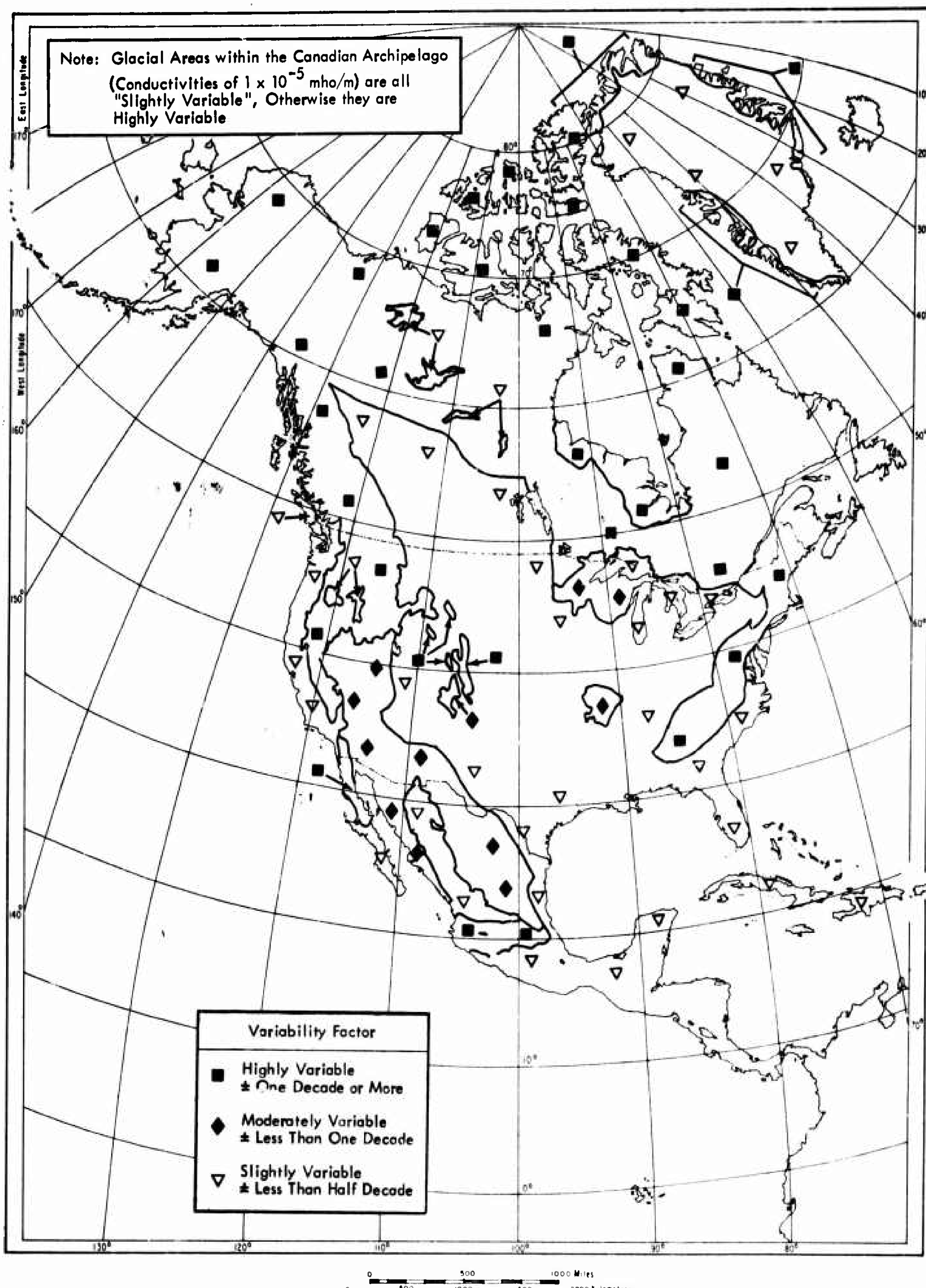


Figure 1B Variability Factor for North America

Figure 2A Confidence Factor for South America

0 500 1000 Miles
0 1000 2000 Kilometers

Figure 2B Variability Factor for South America

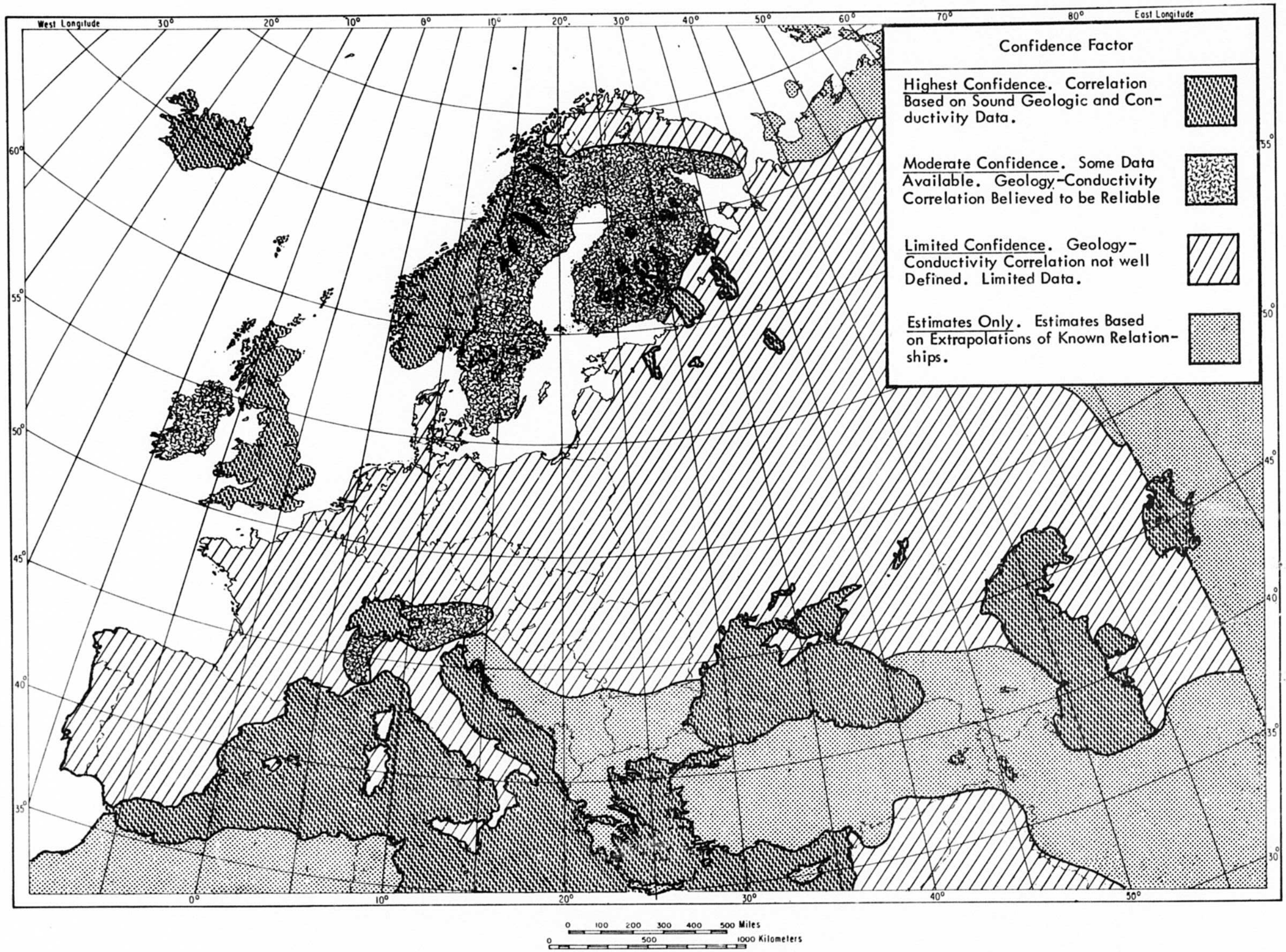


Figure 3A Confidence Factor for Europe

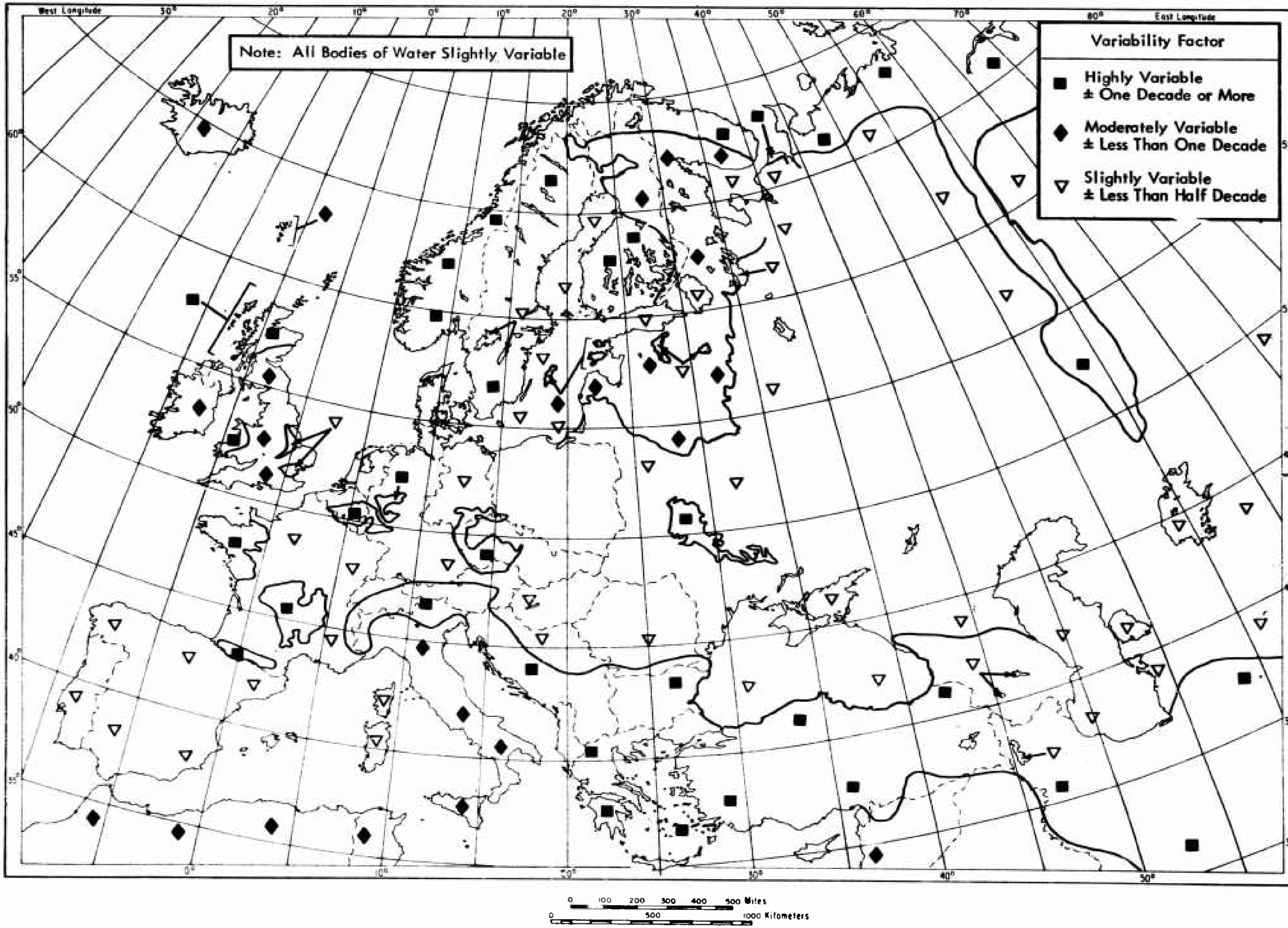


Figure 3B Variability Factor for Europe

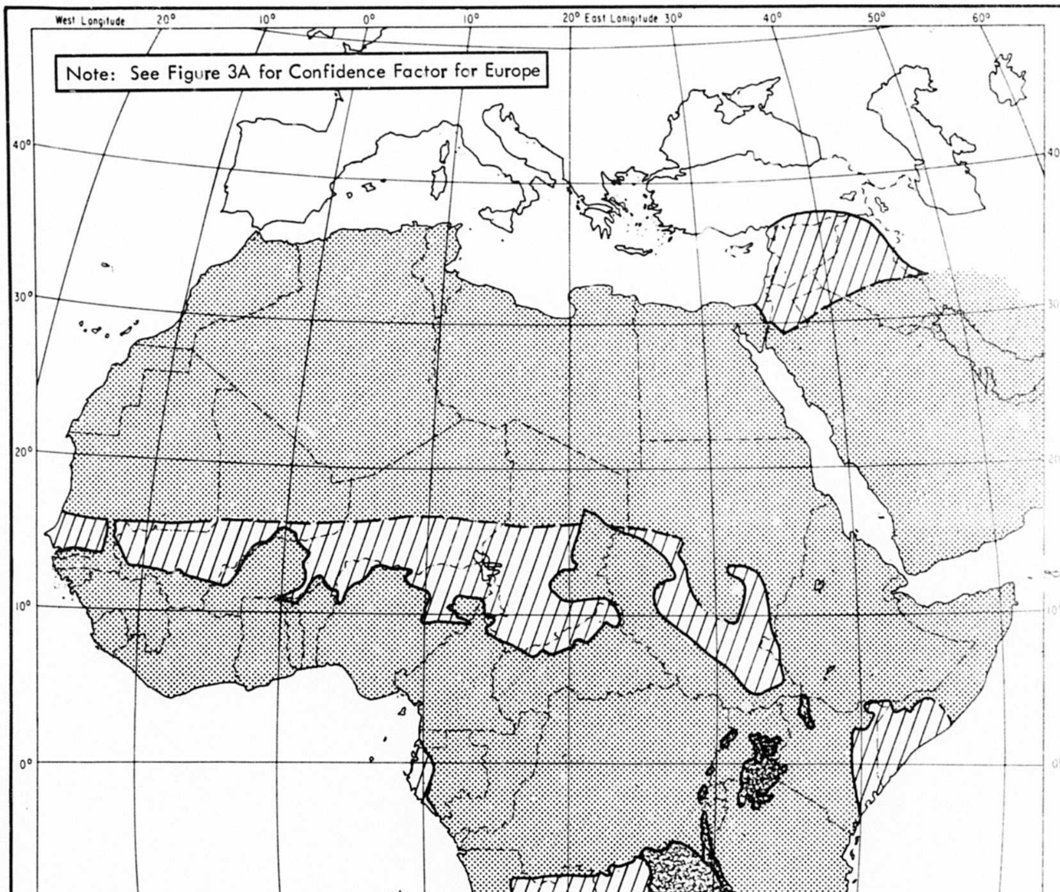


Figure 4A Confidence Factor for Africa

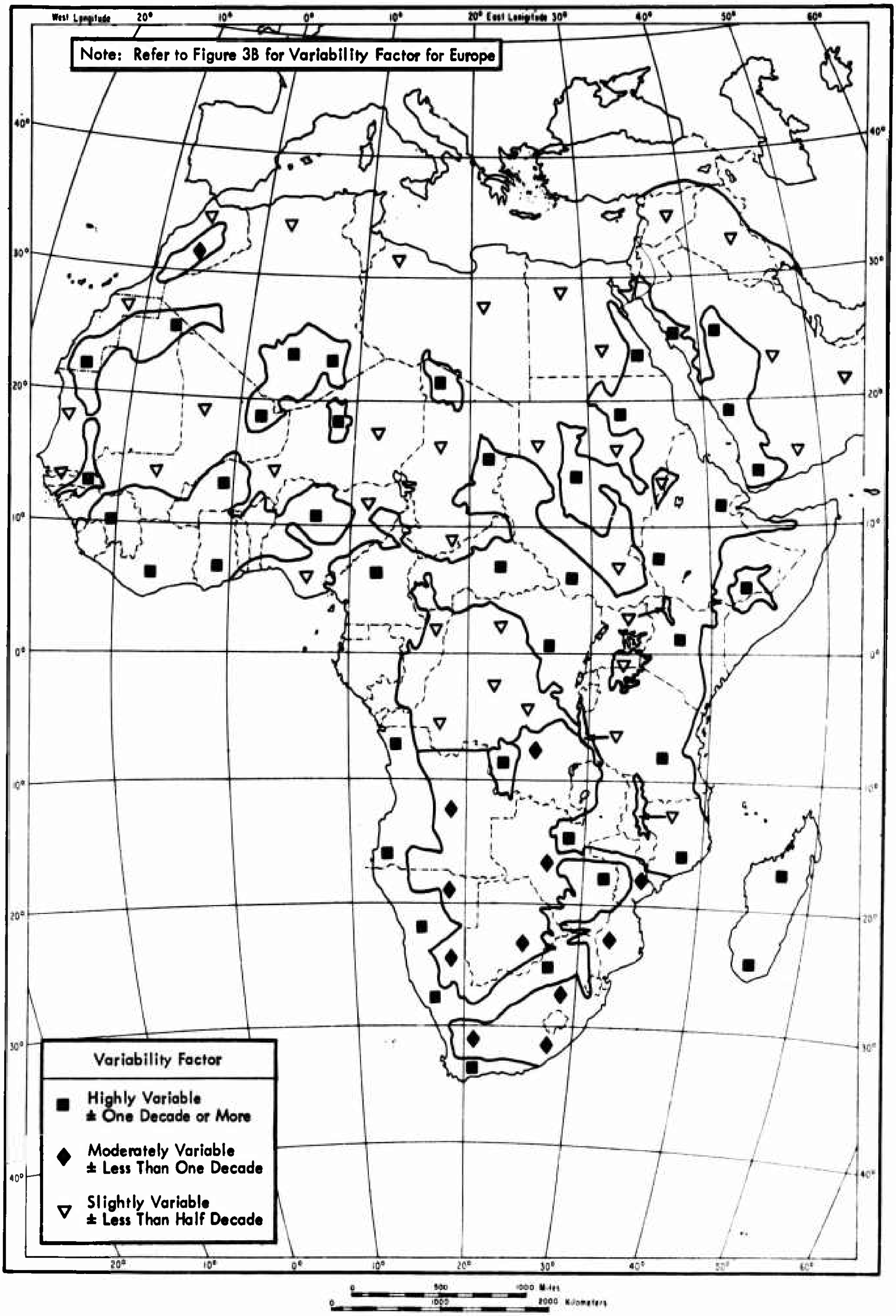


Figure 4B Variability Factor for Africa

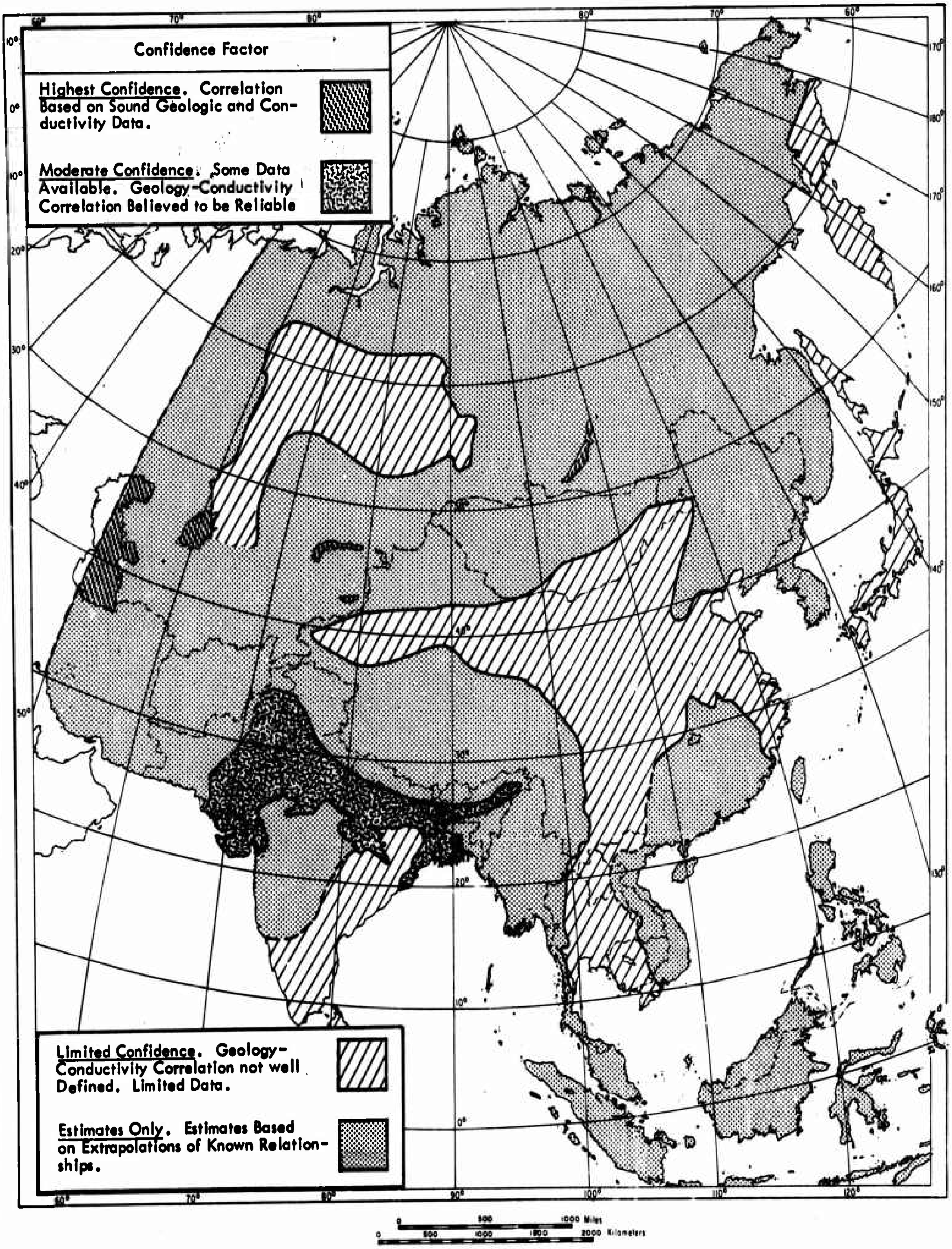


Figure 5A Confidence Factor for Asia

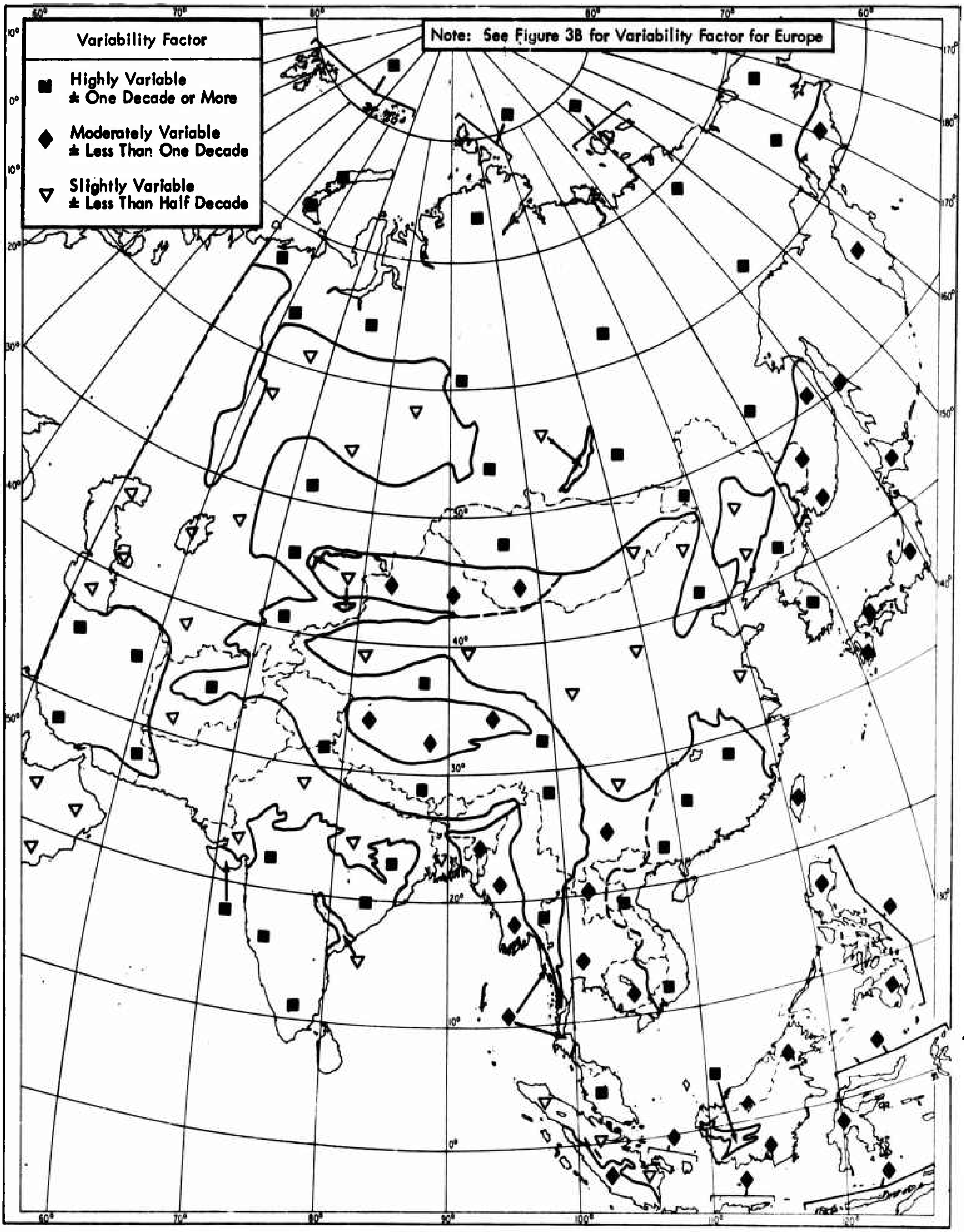


Figure 5B Variability Factor for Asia

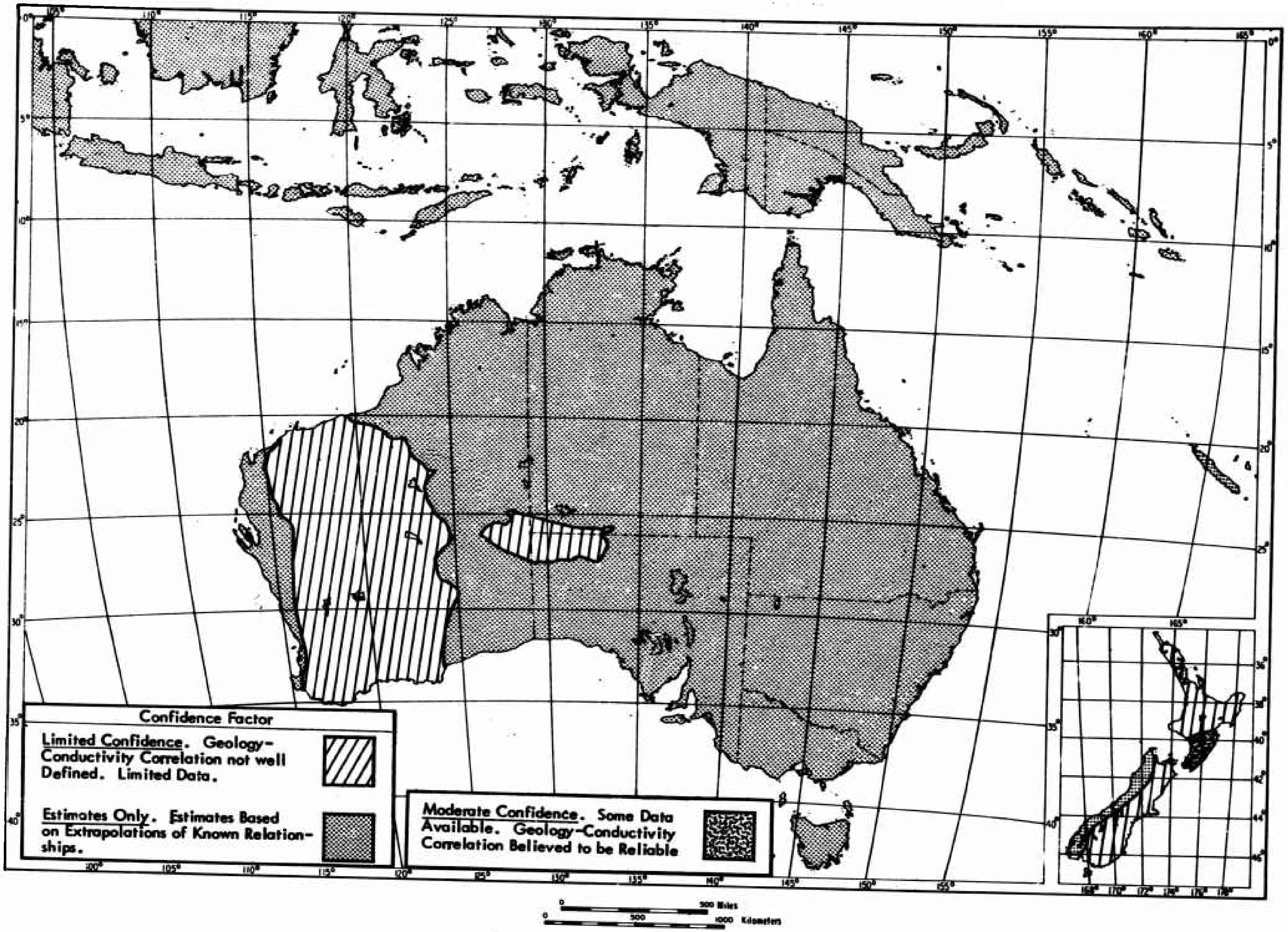


Figure 6A Confidence Factor for Australia

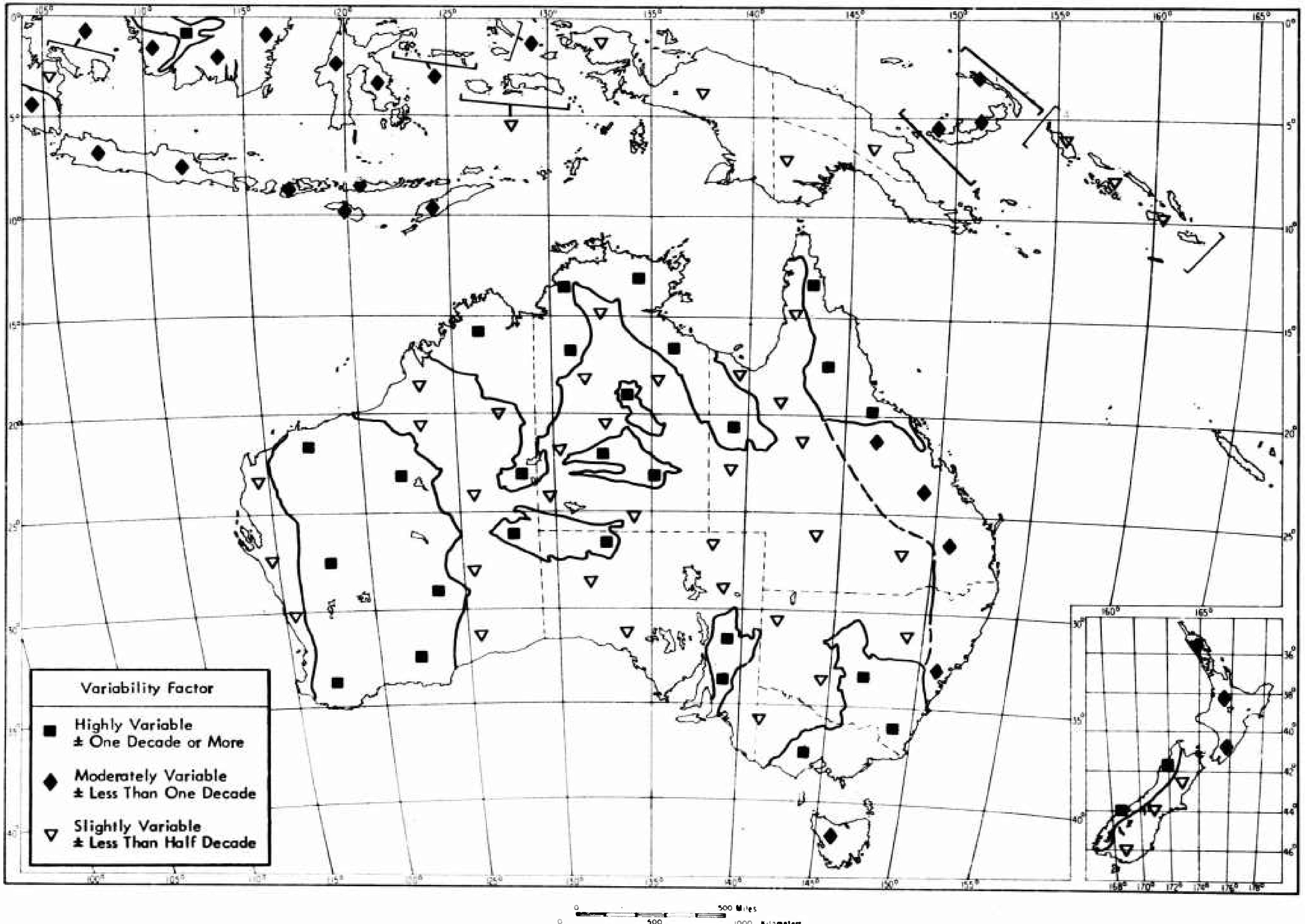


Figure 6B Variability Factor for Australia

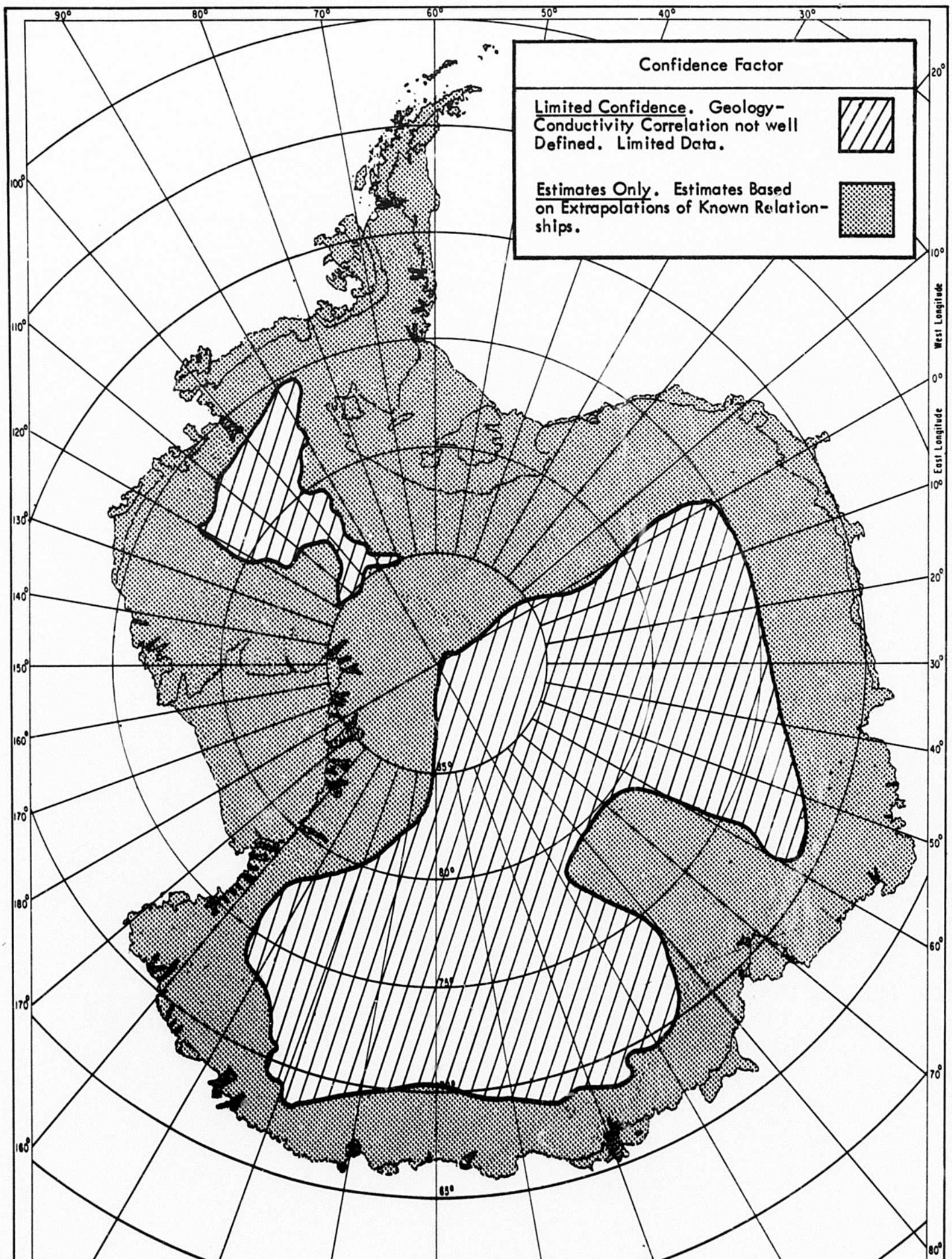


Figure 7A Confidence Factor for Antarctica

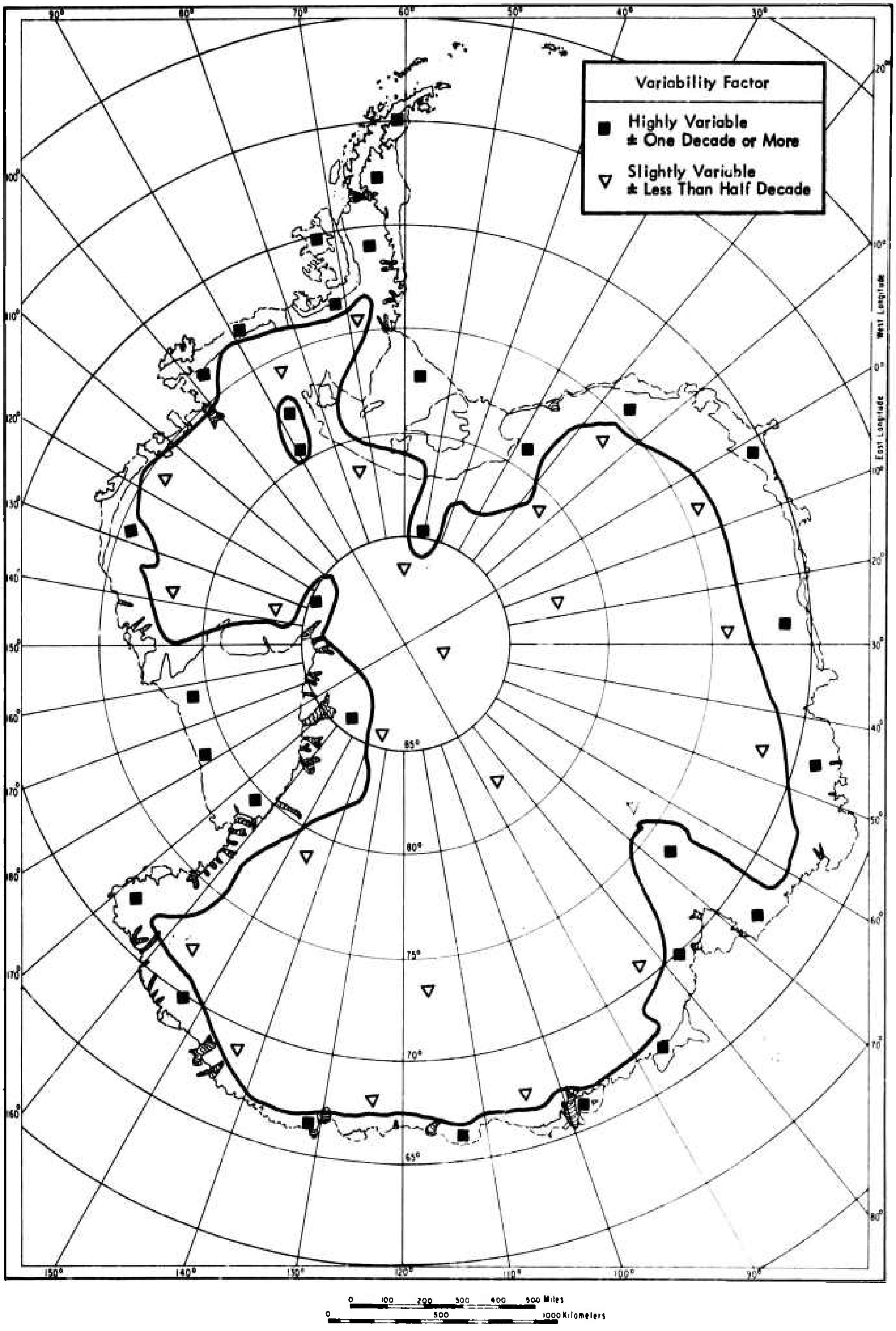


Figure 7B Variability Factor for Antarctica

Estimates Only: Estimates based on extrapolations of known correlations, or on knowledge of conduction mechanisms. These are areas where data is most needed.

Variability Factor

Highly Variable: Variations in local conductivity may be ± one decade or more from the average regional value.

Moderately Variable: less than ± one decade.

Slightly Variable: less than ± half decade.

Important factors relating to the use of the map include effects of "closed lines" where it is evident that energy spreading and defraction can result in less attenuation than would be obtained for a "straight" path between receiver and transmitter. Similarly, transmission across a narrow conductivity contrast which the energy may not circumvent may result in more attenuation than predicted because of energy conversion, reflection, and scattering. Similar effects may be experienced over high rugged mountains, and effects equivalent to one order of magnitude (smaller conductivity) than that attributed to the electrical properties of the materials have been observed for paths across the length of mountain chains. Users should consider the above items in light of the Fresnel spreading of the propagating energy, and the conductivity profile for a propagation path should be determined consistent with this concept, i.e., it is suggested that users consider values of earth conductivity over an area representing the width of the path rather than along a very narrow "line" (great circle) [3].

3.0 EFFECTIVE CONDUCTIVITY

Effective conductivity of a region is defined as the conductivity of a plane, uniform, homogeneous earth which would have the same effect on a propagating electromagnetic field as that of the region. Complications arise for instances where displacement currents in the earth become comparable in magnitude to conduction currents [4] and also for cases where lateral changes result in an anisotropic conductivity in the plane of the surface. These effects were not accounted for in this present work:

1. In most of the land areas of the world, the earth approximates a conductor. Limited data indicate that even for the Greenland Ice Cap, the conduction currents are probably dominant over displacement currents at 10 kHz [5].

2. Only in a few areas was there sufficient data to indicate a difference in conductivity with compass direction. The additional complication of the maps does not justify including this.

Where there was enough information, the magnitude of effective (complex) conductivity was computed for a horizontal layered case [2, Appendix A, also see reference 6].

BLANK PAGE

4.0 ACCURACY OF MAP

Some estimation of the accuracy of the maps for VLF propagation studies may be gained from a comparison of Figures 8 and 9. Figure 8 is a portion of the map of North America, which was produced in 1965 [2]. This map is essentially identical to the northern portion of Sheet 1. Figure 9 shows a revised map based on VLF propagation measurements made in September 1959 and August 1961 (these maps were provided by the U.S. Naval Research Laboratory). Note two significant changes suggested by the NRL Map:

1. The boundary of the "3" region northwest of Hudson Bay should extend further north. This may indicate that the extent of continuous permafrost is further north than previously estimated, or that a thicker deposit of conducting overburden exists in this area.

2. There is an area of "2" conductivity, 3×10^{-5} mho/m, between Labrador and Hudson Bay. This is most likely due to a previously unrecognized occurrence of continuous permafrost. If this area had been so designated, it is noted that the conductivity would have been estimated as 1×10^{-4} mho/m rather than the 3×10^{-5} mho/m as indicated by the NRL Map. Measurements of earth conductivity in this area are therefore suggested.

Other areas can be expected to undergo similar revisions when more data is obtained. These revisions are not expected to be of significance for regions indicated as "highest confidence." Areas similar to the Canadian Shield region which are not well known geologically, and where there is only limited information on permafrost extent and thickness, can be expected to undergo the most extensive revisions.

Further discussion, a list of contributors, etc., may be found in the Appendices which accompany the larger report.

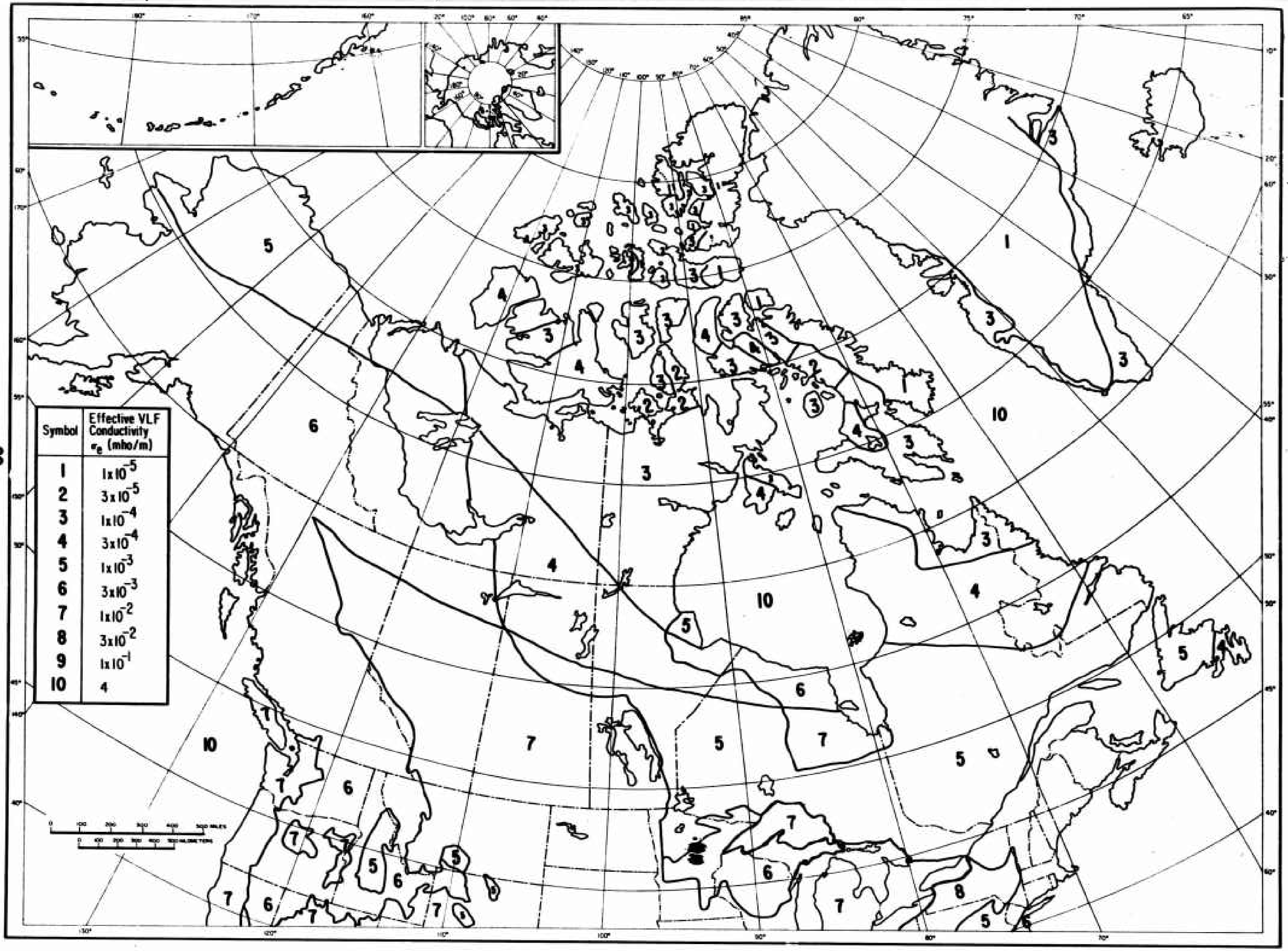
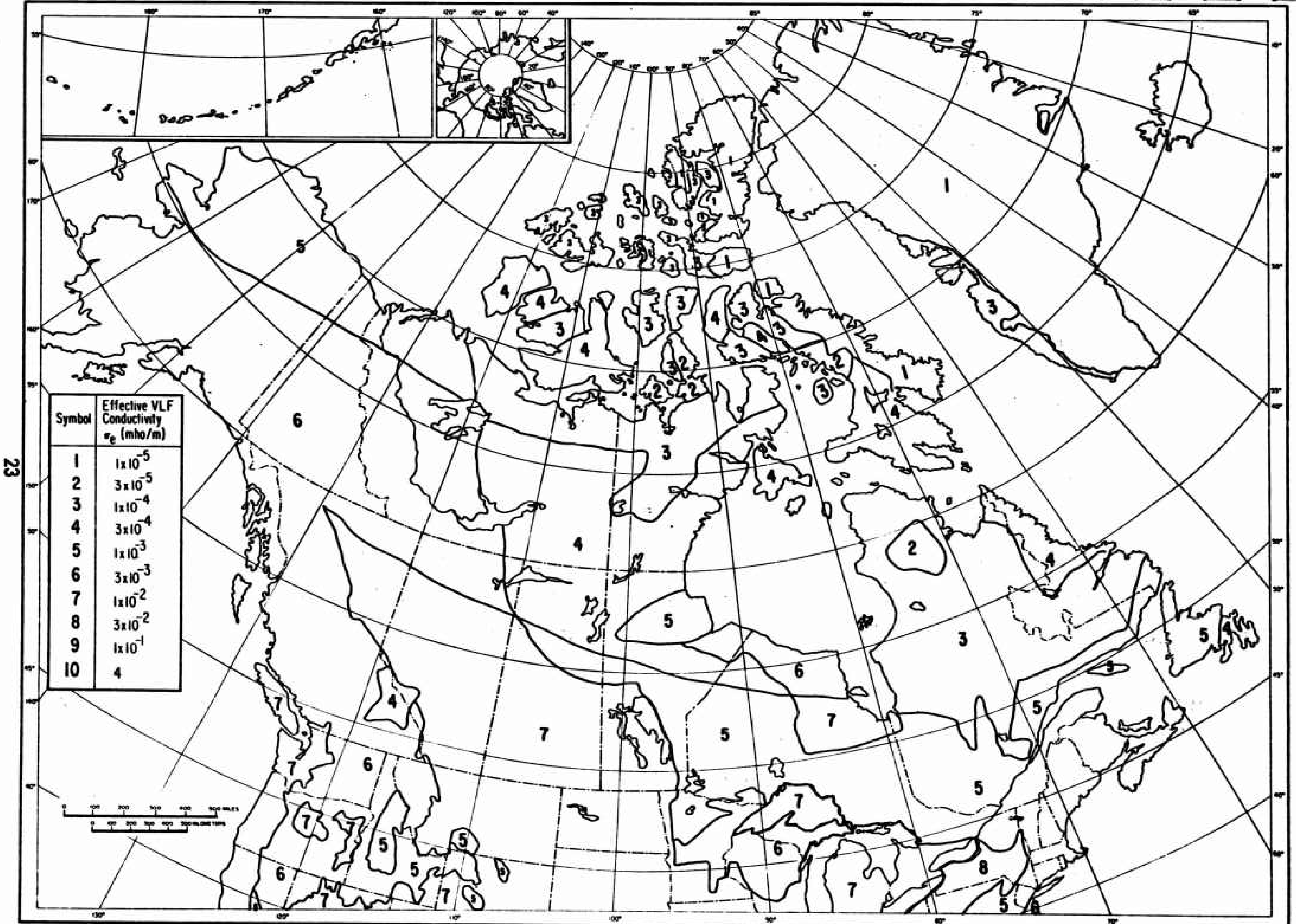


Figure 8 Conductivity Map of Canada.



Symbol	Effective VLF Conductivity σ_e (mho/m)
1	1×10^{-5}
2	3×10^{-5}
3	1×10^{-4}
4	3×10^{-4}
5	1×10^{-3}
6	3×10^{-3}
7	1×10^{-2}
8	3×10^{-2}
9	1×10^{-1}
10	4

Figure 9 Revised Conductivity Map of Canada. Revision by NRL

REFERENCES

[1] Card, R. H., Correlation of Earth Resistivity with Geologic Structure, Trans. AIME, V 138, pp 380-398, 1940.

[2] Morgan, R. R. and E. L. Maxwell , Omega Navigational System Conductivity Map, DECO Report 54-F-1, December 1965, under contract NOnr 4107(00).

[3] Watt, A. D., VLF Radio Engineering, Pergamon Press, New York 1967.

[4] Wait, J. R., The Propagation of Electromagnetic Waves Along the Earth's Surface, appearing in Electromagnetic Waves, R.E. Langer, editor, University of Wisconsin Press, 1962.

[5] Watt, A. D. and E. L. Maxwell, Measured Electrical Properties of Snow and Glacial Ice, NBS Journal of Research, 64D, July-August 1960.

[6] Wait, J. R., Electromagnetic Waves in Stratified Media, Pergamon Press, London, 1962.

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Westinghouse Electric Corporation	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

World-wide VLF Effective-Conductivity Map

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Morgan, Robert R.

6. REPORT DATE 15 January 1968	7a. TOTAL NO. OF PAGES 24	7b. NO. OF REFS 6
8a. CONTRACT OR GRANT NO. N0014-67-C-0274 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 80133F-1 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) None	

10. AVAILABILITY/LIMITATION NOTICES

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research Department of the Navy

13. ABSTRACT

A map showing effective electrical earth conductivity values for a propagating wave at VLF (10 kHz to 30 kHz) has been prepared for the major land areas of the world. Land area conductivity determinations were in most cases based upon known geological and climatological information. Actual conductivity data was collected where possible to aid in determining regional effective conductivity values, but the correlation between geology (and other known factors), and conductivity was used in estimating conductivity for the majority of the land areas.

The conductivity data are overprinted on seven 17 × 22 inch base maps. Effective conductivity values are designated by numbers from 1 to 10 referenced to a legend on each sheet. Separate page-size maps showing a confidence factor and a variability factor are included in the accompanying report.

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Effective Electrical Earth Conductivity						
Correlation Between Geology and Conductivity						
VLF Effective Conductivity Maps						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, *or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification